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Remote Sensing Techniques & Waste Management Assessments

VOLUME I

M.M. DILLON LIMITED
in association with
GARTNER LEE ASSOCIATES LIMITED
and
ONTARIO CENTRE FOR REMOTE SENSING
MINISTRY OF NATURAL RESOURCES

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Ontario Ministry of
the Environment
Waste Management Branch
135 St. Clair Avenue West
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Attention: Mr. J. Petoia
Solid Waste Unit

Remote Sensing Techniques and
Waste Management Assessments

Dear Sirs:

We are pleased to provide our final report on the Applications of Remote Sensing to Waste Management Practices. The Report was prepared in conjunction with Gartner Lee Associates Limited and the Ontario Centre for Remote Sensing.

This research study covers a period of almost two years, from 1979 to 1981. During this time, a great quantity of data was assembled and analyzed. As the information collected was too voluminous for a single report, our research results are presented in two volumes.

Volume I provides a description of the study, a discussion of the results obtained from each remote sensing technique, followed by the conclusions and recommendations. An executive summary is provided at the beginning of Volume I for your convenience.

Volume II is a technical appendix which contains a description of the six landfill sites investigated, and an analysis of the technical data obtained at each site.

We thank you for retaining us to undertake this most interesting research study.

Yours truly,

M.M. DILLON LIMITED

W. F. Wells

WFW:lly

W.F. Wells, P.Eng.
Project Director

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REMOTE SENSING TECHNIQUES
AND
WASTE MANAGEMENT ASSESSMENT

VOLUME I

TABLE OF CONTENTS

VOLUME I

		PAGE
EXECUTIVE SUMMARY		i
1.	INTRODUCTION	1
	1.1 Background	1
	1.2 Study Objectives and Scope	3
2.	A REVIEW OF REMOTE SENSING TECHNIQUES	5
	2.1 General Comments	5
	2.2 Panchromatic Film	6
	2.3 Colour Film	7
	2.4 Colour Infrared Film	7
	2.5 Thermography	9
	2.6 Other Systems	11
	2.7 Electronic Data Analysis	13
3.	PREVIOUS APPLICATIONS OF REMOTE SENSING TO WASTE MANAGEMENT	14
	3.1 General Comments	14
	3.2 Planning and Inventory - Existing Photography	14
	3.3 Monitoring Leachate Discharge	17
	3.4 Landfill Operations Monitoring	20
4.	STUDY METHODOLOGY	23
	4.1 Selection of Sensors	23
	4.1.1 Archival Photography	23
	4.1.2 Photographic Sensors	24
	4.1.3 Thermography	26

TABLE OF CONTENTS
(continued)

		PAGE
4.2	Selection of Candidate Landfill Sites	27
4.2.1	Cobourg	28
4.2.2	Whitby	29
4.2.3	Oakville	29
4.2.4	Bayview Park	30
4.2.5	Burlington	30
4.2.6	Upper Ottawa Street	31
4.3	Data Collection	31
4.3.1	Archival Photography	31
4.3.2	Photographic Sensors	31
4.3.3	Thermography	32
4.3.4	Field Observations	33
4.3.5	Background Data	34
4.4	Data Analysis	34
4.4.1	Photography	34
4.4.2	Thermography	35
5.	STUDY RESULTS	39
5.1	General Comments	39
5.2	Archival Photography	39
5.2.1	Diagnostic Elements	39
5.2.2	Sensor Evaluation	42
5.3	Colour Photography	43
5.3.1	General Comments	43
5.3.2	Leachate Indicators	44
5.3.3	Factors Affecting Detection	48
5.3.4	Sensor Evaluation	50
5.4	Colour Infrared Photography	51
5.4.1	General Comments	51
5.4.2	Leachate Indicators	52
5.4.3	Factors Affecting Detection	58
5.4.4	Sensor Evaluation	61

TABLE OF CONTENTS
(continued)

		PAGE
5.4.5	Comparison of Colour and Colour Infrared Photography	62
5.5	Thermography	64
5.5.1	General Comments	64
5.5.2	Leachate Indicators	64
5.5.3	Sensor Evaluation	68
6.	CONCLUSIONS	71
7.	RECOMMENDATIONS	74
7.1	Assessment of Former Sites	74
7.1.1	Recommendation	74
7.1.2	Background	74
7.1.3	Implementation	76
7.2	Monitoring of Operating Facilities	78
7.2.1	Recommendation	78
7.2.2	Background	78
7.2.3	Implementation	80
7.3	Post-Closure Monitoring	82
7.3.1	Recommendation	82
7.3.2	Background	82
7.3.3	Implementation	83
BIBLIOGRAPHY		

VOLUME II

APPENDICES

APPENDIX A - COBOURG LANDFILL SITE
REMOTE SENSING STUDY RESULTS

APPENDIX B - WHITBY LANDFILL SITE
REMOTE SENSING STUDY RESULTS

APPENDIX C - OAKVILLE LANDFILL SITE
REMOTE SENSING STUDY RESULTS

APPENDIX D - BAYVIEW PARK LANDFILL SITE
REMOTE SENSING STUDY RESULTS

APPENDIX E - BURLINGTON LANDFILL SITE
REMOTE SENSING STUDY RESULTS

APPENDIX F - UPPER OTTAWA STREET LANDFILL SITE
REMOTE SENSING STUDY RESULTS

EXECUTIVE SUMMARY

BACKGROUND

A research project was commissioned by the Solid Waste Unit, Waste Management Branch of the Ontario Ministry of the Environment to evaluate the applications of remote sensing techniques to waste management assessments. A contract was awarded in the fall of 1979 to M.M. Dillon Limited, in conjunction with Gartner Lee Associates Limited and the Ontario Centre for Remote Sensing. The general objectives of the study were to assess the potential usefulness of remote sensing techniques for conducting assessments of waste disposal sites.

REVIEW OF PREVIOUS WORK

To date, practical uses of remote sensing techniques have been generally limited to terrain analyses for the development of site hydrogeological assessments, as a basis for generating contour planning, and to provide a base for site operations monitoring and planning. These have been based largely on black and white aerial photography.

A literature review indicated that remote sensing techniques providing the most useful information were:

- aerial black and white photography
- aerial colour photography
- aerial colour infrared photography
- aerial thermography.

METHODOLOGY

A program was developed to examine the value of each sensor under varying climatic, topographic, hydrogeological, seasonal, and operational conditions. To test applications of remote sensing techniques, each of the above sensors were obtained for six selected sites in southern Ontario:

i) Cobourg, which is an active landfill developed on shallow glaciolacustrine sands and glacial till;

ii) Whitby, a landfill bordering a valley environment and developed on sands overlying glacial till;

iii) Oakville, an active landfill developed on shallow glacial till over shale bedrock;

iv) Bayview Park, a closed landfill developed on shale bedrock;

v) Burlington, an active landfill developed on shale bedrock;

vi) Upper Ottawa Street, a landfill in the process of closing, developed on shallow till over dolomite bedrock.

Archival black and white photography was obtained from the National Air Photo Library and the Ontario Ministry of Natural Resources at available intervals covering the period from the start of landfilling up to the most recent flight.

Colour and colour infrared photography was obtained under contract by Global Remote Sensing Limited of Guelph. The photography at 1:8000 or 1:6000 scale was obtained in March,

April, July and November for each site. Aerial thermography was obtained under contract by Intertech Remote Sensing Limited of Ottawa. This imagery was obtained in March, April and November at an approximate scale of 1:14,000.

Previous hydrogelogical studies and field observations were collected to increase the understanding of remote sensing data and to assist in developing interpretive techniques.

Following each season's data acquisition colour, and colour infrared photography was examined by a magnifying lens stereoscope. Likewise, upon acquisition, archival black and white aerial photography was examined. Analog prints of line-scanned thermography data were also examined after each flight. To further enchance the interpretation of the thermography, some of the imagery was level sliced.

In order to confirm or disprove interpretations made and to familiarize the team members with the site's physical features and topography, periodic field visits were conducted at each site. Distinction was made between ground or surface water and leachate contaminated seepage. Limited temperature data were acquired to assist in assessments of thermography. Field visits were timed to coincide as closely as possible to flight dates.

RESULTS OF STUDY

The investigators found that remote sensing techniques are useful in the search for closed landfill locations, for assessing and monitoring operating facilities and for monitoring closed sites. Of the four systems evaluated, it was found that archival black and white photography was the most cost-effective, the most readily available and the easiest to use for the assessment of landfill sites.

The archival photography provided a time-lapse review of the landfill site and the surrounding environs. This enabled the investigators to interpret the geological environment in which the landfill was set and to evaluate the operation procedures through the years. Conclusions could then be made on the probable off-site impacts of the facilities and predictions of future impacts. For maximum information the interpreters must have a sound background in the terrain sciences, hydrogeology and site operation techniques.

Colour and colour infrared photographs provide information on leachate outbreaks and stress conditions in surrounding vegetation. This photography has to be specially flown and therefore is more expensive. It does, however, allow the investigator to choose the time and scale of the imagery to provide optimum results. We found that a scale of 1:6000 or larger flown in the late spring or early summer was best suited for landfill evaluation in southern Ontario.

Colour photographs flown at large scales can also be utilized to obtain photogrammetric volume measurements for operational control of on-going facilities. This adds a decided cost benefit to using colour. Colour infrared film does not provide a suitable base for the derivation of photogrammetric contour maps and base maps.

Thermography detects thermal anomalies on the ground surface that can be correlated with leachate springs through field verification studies. Although thermal imagery identified some leachate discharges not located on the colour or the colour infrared photography it was found that the thermography had to be supplemented with aerial photographic interpretations and field studies to properly explain all of the thermal anomalies. Thermography is the most expensive of the sensors evaluated for this number of study sites.

CONCLUSIONS AND RECOMMENDATIONS

The research program showed that remote sensing techniques, while not replacing the need for on-site investigations, are useful in the assessment of closed and operating landfills. In all cases, the imagery provides a permanent visual record of previous site activities.

We conclude that archival photography and the method of interpreting it in three dimensions is the most cost effective technique. These black and white photographs are readily available from government libraries and they provide an historical record of the landfilling.

For the monitoring of existing operations, where it is economically justified, colour and colour infrared photography is useful. The sequential monitoring over a number of years of selected large landfills would preferably be done with colour photography.

While the research program showed that thermography can detect subtle thermal anomalies associated with leachate springs, a number of technical and logistical problems arise. These problems are related to the costs of imagery recovery, interpretation of thermal anomalies and the dependability of acquisition systems presently available in Ontario.

For the derivation of maximum information, the interpreter of the remote sensing imagery in use must have a sound background in terrain sciences, hydrogeology and site operations techniques.

Finally, the report contains recommendations for the implementation of three remote sensing programs associated with waste management within the Province. These programs are:

- assessment of former landfill sites
- monitoring of operating facilities
- post-closure monitoring.

Archival photography is recommended for the assessment of former landfill sites and a program is recommended whereby these techniques can be integrated into the Waste Identification Study recently undertaken by the Ministry.

The monitoring of operating facilities will require an annual photographic mission over selected large landfills within the Province. The exposure of colour and colour infrared is recommended on these missions.

The post-closure program is designed to expose colour and colour infrared over landfills previously designated as having potential impact on surrounding lands.

1. INTRODUCTION

1.1 Background

In late 1979, the Solid Waste Unit; Waste Management Branch of the Ontario Ministry of the Environment awarded a research study to M.M. Dillon Limited, in conjunction with Gartner Lee Associates Limited and the Ontario Centre for Remote Sensing. The study was to evaluate the applications of remote sensing techniques to waste mangement assessments - specifically landfill disposal, traditionally the most common disposal method in Ontario.

Aerial photography has been used in the initial planning stages for landfill siting for many years. However, research in the northeastern United States and a pilot study in southern Ontario indicated remote sensing techniques could also be used in detecting leachate discharge from landfill sites. Therefore, the consultants were to evaluate;

i) the suitability of extending the application of current remote sensing techniques to landfill management and,

ii) the incorporation of such techniques into the programs administered by the Ministry.

In evaluating the techniques, several specific applications were considered. Firstly, we were to evaluate the use of remote sensing in the inventory of former (closed or inactive) landfill sites. In 1979, the Ministry was beginning a program to identify the location of former landfills throughout Ontario. The majority of these municipal and industrial sites operated prior to 1971, before Ministry of

the Environment (MOE) regulations of waste disposal practices were in effect. Sites were often small, with little or no control over their operations. Location depended more on land ownership and proximity to waste generators than on environmental concerns. When a site was full, earth fill covered the refuse and the lands were abandoned or put to a new land use. Records, if kept at all, were usually incomplete. Therefore, the Ministry realized that their 1979 inventory, based on existing records and public recall could be incomplete. Remote sensing, specifically historical (archival) aerial photography, was a potential technique to improve the accuracy and completeness of the inventory.

Secondly, landfills in Ontario produce leachate (as a result of water percolating through the refuse) and methane gas (as a result of refuse decomposition). Depending on the physical setting - soils, ground and surface waters - these landfill products can affect the surrounding environment for some distance down gradient of a site. The concern of the Ministry to control potential impacts led to the design of leachate collection systems for most landfills constructed or closed since the mid-1970's. However, the effectiveness of these new engineering designs needs to be evaluated over time. Therefore, remote sensing techniques were to be examined as a potential tool for monitoring leachate and gas discharge from closed and active sites.

Finally, the actual operations of landfills were becoming more sophisticated and efficient. Operating procedures needed to be monitored to ascertain that efficiency was maintained and performace evaluated. Remote sensing techniques were to be considered as a potential part of monitoring and evaluation procedures.

Based on this background of previous research and applications the consultants developed a program to evaluate remote sensing as it applied to waste management in Ontario.

1.2 Study Objectives and Scope

The objectives of the research project were:

- to review existing and potential applications of remote sensing to landfill waste management;

- to evaluate remote sensing techniques for -

    - former site inventory
    - monitoring environmental impacts (leachate, gas migration)
    - monitoring site operations
    - assisting in waste management planning and site location

- to recommend the suitability of specific remote sensing techniques for Ministry waste management programs.

In keeping with the applied nature of the research project, the techniques examined were to be commercially available to the government agencies implementing the surveillance programs. The four techniques selected - existing (archival) black and white aerial photography, current colour aerial photography, current colour infrared aerial photography and current thermography were tested on six landfill sites and the results evaluated for the:

1. value and reliability of the data generated,

2. level of technical expertise require to interpret results,

3. cost of acquisition, and

4. compatibility of data format with other information gathering programs.

2. A REVIEW OF REMOTE SENSING TECHNIQUES

2.1 General Comments

Remote sensing may be defined as the detection, recognition or evaluation of objects by means of distant sensing or recording devices (Avery, 1968). These devices record both reflected and emitted energy. Figure 1 shows the electromagnetic spectrum and some of the sensors that are used to record this energy.

Within the reflected portion of the spectrum, conventional cameras and films are used to record the photographic part of the spectrum, from about 300 nanometres (nm) to about 1500 nm. This range is from the near ultraviolet to the near infrared, including the area of visible light. Examples of remote sensing devices recording within this part of the spectrum are panchromatic and colour aerial photographs, black and white and colour near infrared images and multispectral images.

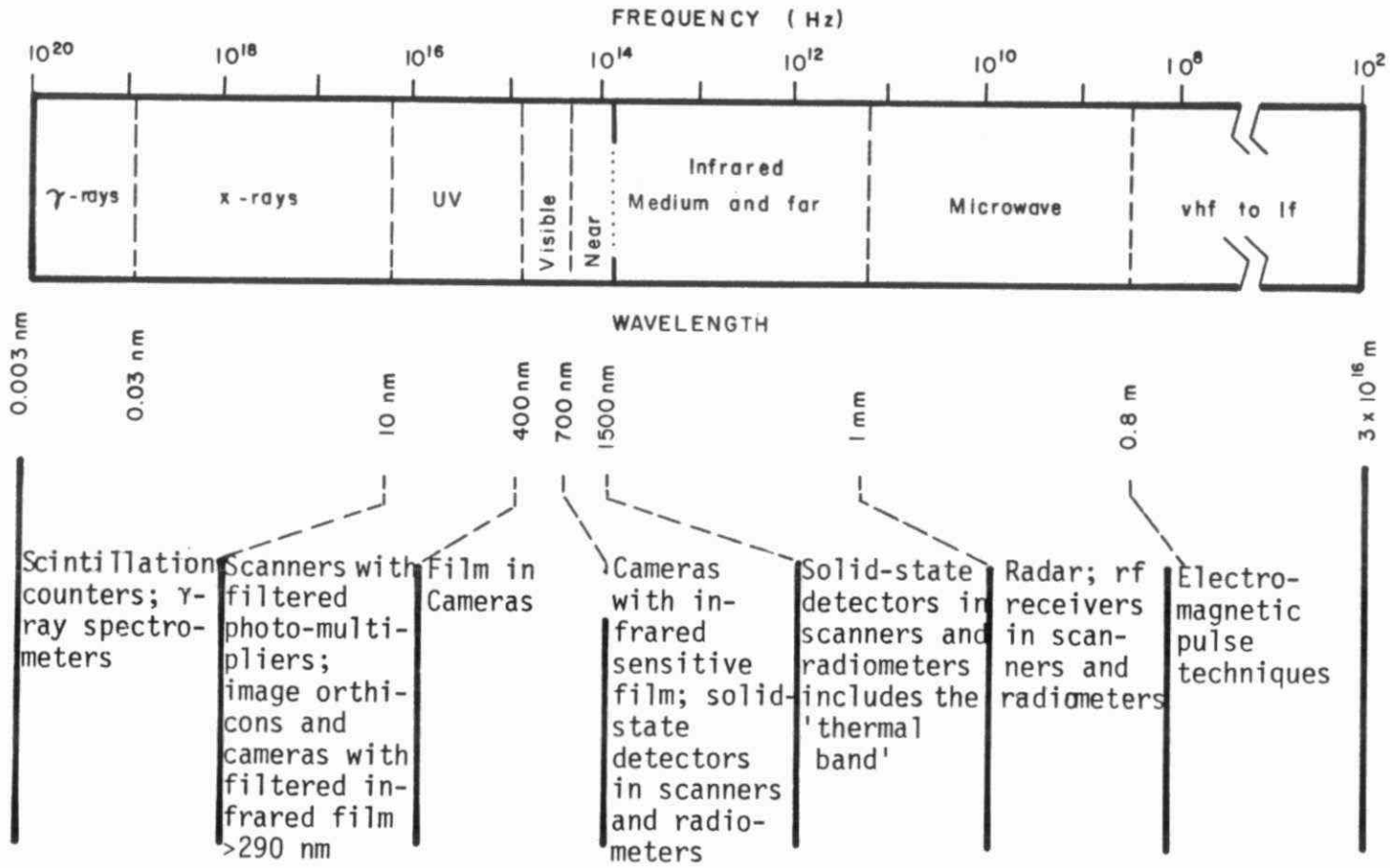
The x-rays, gamma-rays and far ultra-violet wavelengths are sensed using scanners with photo multipliers, counters and spectrometers.

At the high end of the electromagnetic spectrum, the energy is emitted rather than reflected and the recording devices are in the form of solid-state detectors in scanners and radiometers, radar receivers and a variety of electromagnetic pulse techniques. Included in this group are the thermal scanners that record emitted heat energy, i.e. thermography, in the medium and far infrared wavelengths.

Past research has shown that only a few of the systems of this impressive array of remote sensing hardware can be usefully applied to waste management. These systems include:

Figure 1

REMOTE SENSORS FOR THE ELECTROMAGNETIC SPECTRUM



The Electromagnetic Spectrum and Some Sensors that Use it. The infrared portion of the spectrum, though much wider than the band of visible radiation, is still a small part of the total. Recent research has focused on the integrated use of several sensors, each making use of a different portion of the spectrum.

SOURCE : Bird & Hale , 1977 ; pg 22.

1. Panchromatic film
2. Colour film
3. Colour infrared film
4. Thermography

For a complete appraisal of the state-of-the-art in remote sensing and a description of the sensors and their capabilities the reader is referred to the Manual of Remote Sensing (Reeves, ed. 1975), the Ministry of Transportation and Communications, Ontario Research Report 209 (Bird and Hale, 1977), and other publiciations listed in the bibliography to this report. Only a brief review of the sensors is provided in the next sections of this chapter.

2.2 Panchromatic Film

Black and white panchromatic aerial photographs are the most common form of remote sensing data available today. Photographs at a variety of scales and from a number of different years are available in government libraries across Canada. Ontario photographs are available from the Ministry of Natural Resources Air Photo Library in Toronto and from the National Air Photo Library in Ottawa.

These photographs are taken along pre-determined flight lines and can be viewed stereoscopically to produce a three dimensional model of the terrain. When properly interpreted, they show a variety of surface conditions that can be directly related to waste management conditions on the ground.

The advantages of these panchromatic photographs over all other remote sensing techniques, is their availability, their low cost and the ability to compare one year's photography with that of another year (i.e. archival photography).

2.3 Colour Film

Aerial colour films are composed of emulsion layers, each one sensitive to a different primary colour, i.e. red, green or blue.

The main advantage to the use of colour photographs instead of panchromatic film is that the interpreter can distinguish considerably more colour hues than grey tones. This is a distinct advantage when the detection of certain features on the photographs is colour dependent - such as red-brown leachate.

Although more and more areas of the province are being contract flown in colour every year, colour photographs are still not readily available for many areas. It is advisable, however, to use colour film as opposed to black and white film if special flying is required for any specific purpose.

The techniques of interpretation of colour aerial photographs are similar to those for panchromatic films, but the colour adds a further dimension that can enhance the information gathered from the imagery.

2.4 Colour Infrared Film

Most reflected infrared radiation is in the 700 nm to 1300 nm range (near infrared), and can be sensed photographically,

using infrared-sensitive films. This produces a "false colour" image that records the reflected energy in these wavelength bands - a range that is invisible to the human eye.

The advantages of colour infrared (CIR) are that it allows the interpreter to evaluate stress conditions in vegetation that may be invisible to the human eye, and it enhances wet areas and water bodies.

As an example, a plant leaf has a naturally high IR reflectance due to its internal structure. When the vegetation is stressed by disease, insect infestation or other causes, the internal cell structure of the leaf begins to collapse and the IR reflectance drops. This shows on the colour infrared photograph as a darker than normal red colour, and this initial loss of IR reflectance is called a previsual symptom of plant stress. Advanced plant stress produces a cyanic colour on the film (Sabins 1978).

White and yellow signatures on the colour IR film can also reflect late autumn conditions when the leaves have changed colour from green to red and brown.

Another characteristic of the colour IR is the high absorbance of the IR radiation by water, resulting in dark blue or black signatures that contrast to the red of vegetation (Sabins 1978).

Some characteristics of colour infrared film create problems in obtaining consistent results when exposing the film (Fleming, 1980). The IR sensitivity is difficult to control at the manufacturing stage, and more difficult to preserve in storage and handling. In different film emulsions, the infrared layer can react by providing different colours in

combination with the other two colours - forming layers of the film. This colour balance is also affected by the altitude from which the exposure is made, and the exposure setting. These problems, however, can be overcome by following strict procedures as reported by Fleming (1980).

Thus, colour IR has a number of advantages when interpreting vegetation, but also has some drawbacks due to the inherent make-up of the film emulsions.

2.5 Thermography

Thermal infrared energy is emitted by any material substance having a temperature above absolute zero (-273°C). This means that all objects on the earth's surface radiate heat energy. The radiant temperatures emitted by these bodies will vary, dependent upon the emissivity characteristics of the object. Sensors have been developed to measure these differences in radiated heat energy - referred to as thermal sensing systems. These thermal wavelength bands begin at about 1.6 micrometres (um) on the electromagnetic spectrum. The sensors generally operate within either the 3.5 to 5.5 um range or the 8 to 14 um range.

The size and sensitivity of the detecting element governs the unit's thermal and spatial resolution. Systems presently available for civilian use are sensitive to radiant temperature changes as small as 0.2°C over a spatial resolution element of 1 m per 1000 m from the object. An average temperature is sensed over this area.

Thermal infrared sensing may be achieved through use of the following types of sensors:

a) line scanners
b) imagers
c) radiometers
d) television cameras (pyroelectric vidicons)

The infrared line-scanner mode of operation is illustrated in Figure 2. A small sensor element is swept across a path, perpendicular to the aircraft flight line, by means of a rotating 40° mirror. The field of view produced may vary between 60° to 120°, depending on the sensing system. The radiation is measured and then either stored on magnetic tape for later processing, or used to modulate a cathode ray tube, used to focus on photographic film. As the aircraft flies forward, a series of lines are accumulated on the film, from which a trip map of the terrain beneath the aircraft can be produced. Some infrared scanners are equipped with calibration sources in order that an absolute measurement of temperature can be made.

Infrared imagers form a real-time, frame-type image of the infrared radiation from the area under observation. They differ from line scanners in that they scan in two directions - line scan and field scan - thus producing an image without the requirement of platform motion. The signal measured at the detector for each resolution element is then used to modulate the output beam of a cathode ray tube, much in the same manner as in a television system. The temperature range of interest can be selected manually and an image of the intensity of infrared radiation will form on the imaging tube. The image can then be photographed or observed directly. Some imagers provide for data storage on digital tape.

Radiometers are non-imaging devices which measure the value of emitted or reflected energy. A radiometer may be

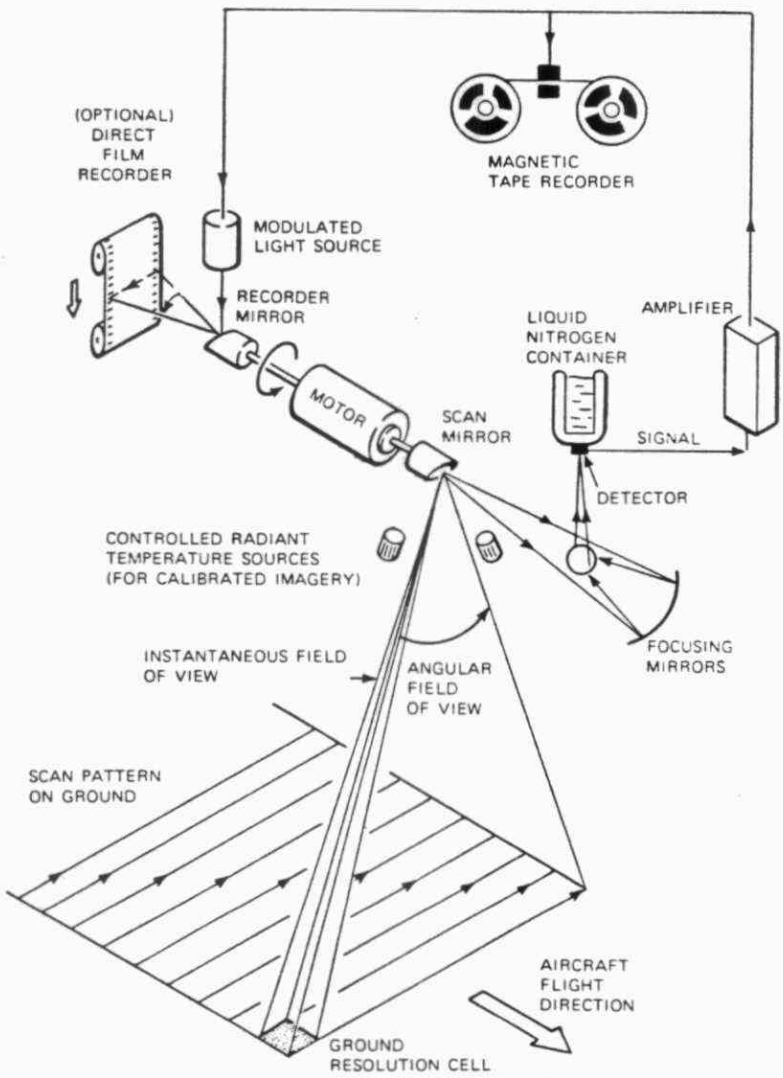


Figure 2 - Schematic representation of the operation of a thermal line scanner. As the scan mirror sweeps across the flight path, the optics focus the incoming energy onto the detector element. The signals produced at the detector are stored on tape for later processing or can be used to create an inflight copy of the data (after Lillesand and Kiefer, 1979).

sensitive to energy from the ultraviolet to the far-infrared region (0.3 to 14 um). The readings from a radiometer operating in the thermal emission range of the spectrum can be converted directly to temperature if the emissivity of the object sensed is known. The radiometer is mounted to point vertically down from the aircraft, and produce a chart indicative of the temperature of the terrain along the flight line, with an absolute accuracy of $\pm$ 0.5°C (see Figure 3).

A television camera system, the 8-13 micrometre Pyroelectric Vidicon, has recently become available to civilian users. Pyricon tubes produce a relatively high contrast image of a thermal scene on the screen of a black and white TV monitor. They are useful for the recognition of thermal patterns, but do not provide a numerical rating of temperature.

Thermography is useful in the study of landfills because of its ability to detect thermal anomalies that can often be related to leachate springs.

2.6 Other Systems

Electronic systems are not limited to the thermal band. The Landsat-series of earth resource satellites are equipped with electronic sensing systems sensitive to the green, red and two infrared bands of the spectrum. The satellite systems provide a regional overview of the earth's surface.

Multi-spectral systems are also available for airborne operations. These systems are designed to record energy from many spectral bands, all at the same time. The Environmental Research Institute of Michigan and Daedalus Enterprises

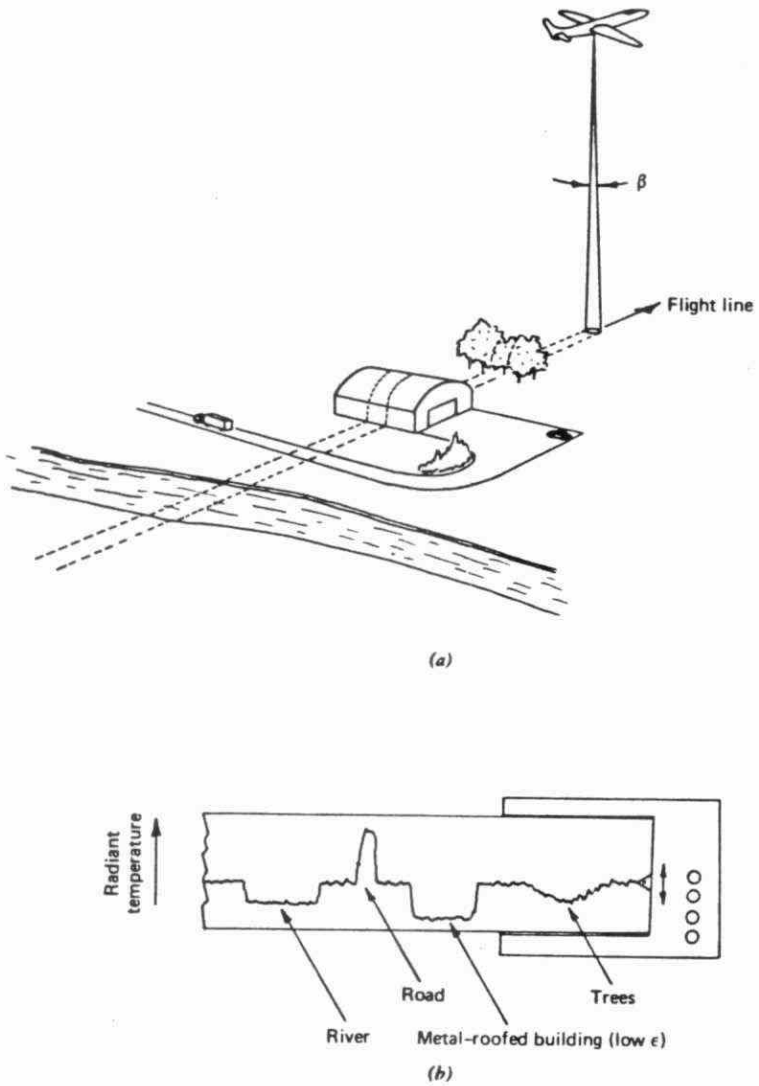


Figure 3 - Radiometers look at only a single spot on the ground. Combined with the movement of the aircraft, a single line of radiant temperature data from directly beneath the aircraft is recorded (after Lillesand and Kiefer, 1979).

Limited, both of Ann Arbor, Michigan, U.S.A., produce multi-spectral systems of seven and twelve channels, respectively.

Airborne multi-spectral electronic sensors are recent additions to the remote sensing arsenal and have yet to be fully explored.

Vidicon tubes (television-type cameras) are available that are sensitive to the ultraviolet, visible, near-infrared and far (thermal)-infrared portions of the spectrum. The output from the tube is recorded directly onto video tape. The resolution of the data is governed by the television format and is poorer than that provided by aerial photographs. Vidicon systems do, however, produce "real-time" images of the scene under view.

Radar sensors, which have the ability to penetrate cloud cover, consist of a transmitter which sends radar signals down to the earth's surface, and a receiver to detect the waves that bounce off objects and return to the aircraft. After the flight, the recorded energy returns are processed into visual imagery, which represents varying concentrations of signal return by shades of grey. Generally speaking, smooth surfaces bounce the radar signal away from the receiver, while rough surfaces deflect the signal so that it may be recorded by the sensor.

Imaging radar systems have only recently become available to the remote sensing community and their potential use is still being investigated.

2.7 Electronic Data Analysis

Analog image analysis is the electronic detection of small differences in the recorded signal and the discrimination of these differences as a secondary image output. When the original image is produced on a photographic emulsion, areas of similar tonal density can be separated and displayed as distinct colours on the output screen. This is known as density-slicing. Because of man's limited ability to distinguish between grey shades very near each other, density- slicing provides a method for gaining increased information from remotely-sensed data. Another form of electronic analog image analysis is applied to thermography data. In this instance, areas of equal temperature can be displayed as distinct grey levels on the image output. The temperature level-sliced data provides a "heat map" of the terrain under review.

Computer digital analysis of remote sensing data enables the maximum amount of detail to be derived from the imagery. The image is broken into single picture elements or "pixels". The computer is then instructed to locate all similar pixels. The computer can also overlap various types of remote sensing data, as well as data from different seasons. Computer analysis can be applied to producing maps, calculating areas and volumes, and providing for other remote sensing needs.

3. PREVIOUS APPLICATIONS OF REMOTE SENSING TO WASTE MANAGEMENT

3.1 General Comments

Remote sensing has been applied to waste water management problems for more than a decade. Much of the research has concentrated on techniques to identify and monitor pollutant discharges into rivers, lakes and oceans. Generally, these studies deal with a specific or known group of pollutants (e.g. oils, sewage sludge, industrial plant effluents), and researchers have developed visual and non-visual techniques to determine the origin, nature and dispersion of these pollutants (see appended references).

On the other hand, however, specific interest in remote sensing techniques to monitor the land disposal of solid wastes is relatively new. Recently, traditional use of aerial photography for the location of waste disposal sites has expanded into site inventory and operations monitoring (Wells and Bourque, 1980). Current research examines more specialized techniques, such as colour infrared photography and thermography, for monitoring closed landfills.

3.2 Planning and Inventory - Existing Photography

Aerial photography is used for planning waste management systems in both Europe and North America. Geological conditions and current land use data are interpreted from existing photography and suitable waste disposal areas are selected for future detailed ground studies (Enslin et al. 1977; Gartner 1980; Gibson 1978; Hunt 1975; Vass and

Van Genderen 1978; Schneider 1977). These data are of particular importance in areas of ground water concerns or areas of special geological settings (Brooks et al 1977; Harvey et al 1978).

Interpretation of aerial photography can also identify probable sources, types and volumes of wastes generated in a region. These data can then be used in the design of waste collection systems, in the identification of the number of sites required and even in assessment of the potential recoverable energy from landfills (Garofalo and Wobber, 1974; Garofalo and Martin, 1977). Stereoscopic interpretation of panchromatic aerial photography (scale 1:10000 to 1:50000) is the standard technique used for these studies. To date, colour infrared and colour photography, Landsat imagery and thermography have only been used for specific studies, and on a limited basis.

Since the mid-1970's available black and white photography has been employed to provide an inventory of existing and closed landfill sites. This new application of the photographic record is a response to the greater awareness of the health and environmental hazards posed by these sites.

A massive inventory program is currently in progress across the United States as the first phase of a $1.8 billion Environmental Protection Agency program designed to identify and clean-up existing and unknown hazardous waste dumps (V. Webb, personal communication). Two hundred communities, where hazardous wastes are generated, are being examined. For each community, the inventory process begins by a comparison of surface disturbances visible on the most recent photography and the earliest available photography. Subsequently, photography from the intervening years is

interpreted to build a case history of these disturbed areas, to determine the nature and extent of any possible disposal activity. Following indentification, all potential disposal sites are field checked. As a result of this inventory, six hundred (600) potential disposal sites were located around one community. Of the one hundred and twelve (112) that have been field checked, twenty-eight (28) contained hazardous wastes.

Another smaller example of the use of existing photography is an inventory of closed landfill sites around the City of Ottawa, Ontario in 1980 (Gartner Lee Associates unpublished). Although some sites could be located from municipal records, interpretation of aerial photography, dating from 1920 to the present, located unknown sites and identified the exact extent of the refuse. This facilitated later field work.

Similar success in identifying and accurately locating disposal areas with available photography has been reported from studies in New York State (Anonymous 1976b), Louisiana State (Hill and Trivedi 1980), and England (Bush and Collins 1974; Gibson 1974). In all cases, interpretation of aerial photography identified more sites, existing and closed, than were identified by municipal records or through public surveys.

In addition to locating legal sites, several authors cite locating illegal or poorly maintained landfilling activity when analyzing recent photography (Hill and Trivedi 1980; Schneider 1977; V. Webb, personal communication).

Further to locating the existence of landfills archival photography can locate zones of possible leachate impact from landfill sites (Sangrey and Philipson 1979; Erb et al, in

press). These impact areas can be determined from interpretation of the pre-landfill geological conditions. Such information can be particularly important if urban development has obscured the surrounding conditions and the landfill. In this case, archival photography can be the most rapid means to determine where potential health hazards are likely to be located. An example of such a situation is illustrated by work at the Love Canal, Niagara, New York State. Analyses of archival photography was instrumental in the rapid initial evaluation and design of the subsurface investigation program (Anonymous, 1979a).

3.3 Monitoring Leachate Discharge

To date, examination of remote sensing applications to the monitoring of landfill impacts has concentrated on detection of leachate discharge using specially acquired data. The main remote sensing techniques are colour photography, colour infrared photography and thermography. While the interpretation of existing panchromatic photography can often predict where impacts will generally occur, it does not locate actual impacts.

Souto-Maior (1973) studied the use of thermography in detecting contaminated ground water discharge from a landfill in Wisconsin. The landfill is developed in clay soils and is bounded by a small stream. A shallow leachate mound has developed in the refuse. Unfortunately, several problems were encountered interpreting the thermal data: dense vegetation around seepage areas, the size of warm seepage anomalies, the lack of temperature contrast between

leachate and natural ground water, and constant surface disturbances on the active landfill inhibited clear detection of discharge areas on the thermography.

A recent Canadian study examined applications of several photographic sensors at a southern Ontario landfill (Ontario Centre for Remote Sensing, 1978). Colour and colour infrared photographs at 1:6000 scale were useful in detecting leachate streams and vegetation stress respectively on the site. Both positive (healthy cattail growth) and negative (damaged trees) stress was visible. Black and white infrared photography and a photography scale of 1:14000 were both found to be less suitable and such data were acquired for only one season.

However, the most comprehensive investigation of landfill monitoring to date is a United States Environmental Protection Agency funded study to develop a remote sensing technique for detecting ground and surface water contamination by leachate (Sangrey et al, 1975; Philipson and Sangrey, 1977; Sangrey and Philipson, 1979). Colour photography, colour infrared photography, and thermography were acquired for twenty sites in the northeastern United States. Specially acquired remote sensing data were collected from missions flown at different altitudes and in all seasons.

The study found that leachate was rarely observed directly, but that detection was usually through an evaluation of environmental effects, such as gaps in ground cover (snow or vegetation), surface wetness, vegetation stress and colour anomalies. The ability to detect leachate contamination also depended on:

a) the nature of leachate discharge from a landfill; remote sensing techniques were useful only if leachate discharged at surface creating some surface effect;

b) the season; leachate production rates and vegetation conditions (as an indicator of stress and as a means to obscure impacts) changed throughout the year; and

c) site age.

Aerial photography at a scale of 1:5000 was generally the most useful sensor, with colour infrared film being most suitable if only one set of imagery could be obtained (Sangrey and Philipson, 1979). Late spring or autumn was found to be the best time to acquire data. As in the Ontario Centre for Remote Sensing Study (1978), leachate staining was clearest on colour photography while colour infrared photography identified vegetation stress.

Thermography was useful when leachate springs were warmer than surrounding areas. No single sensor detected all leachate sites; although a combination of data gave increased accuracy by confirming outbreaks (e.g. thermography distinguished which wetness areas visible on the photographs are warmer). However, Sangrey and Philipson (1979) note that existing photography can also be used to detect leachate discharge in addition to its application for planning of landfills.

No work has been done on direct remote sensing detection of leachate. Extensive work has been carried out developing techniques to monitor specific chemicals or groups of chemicals in water (e.g. Washburn and Sandness, 1977; Watson et al, 1975; Philpot and Klemas, 1979; Johnson et al, 1979; Bristow, 1978). In addition, many authors have also

investigated remote sensing techniques, mainly colour infrared photography, to detect and monitor effects of toxic concentrations of elements (e.g. salinity) in soils on crops (Myers, 1975; Myers et al, 1970; Halstead and Rennie, 1972; Dalstead and Worcester, 1979). However, the numerous variations and problems encountered in these studies indicate that specific sensing of leachate, with its highly variable chemical composition, is not at present viable.

3.4 Landfill Operations Monitoring

Landfilling operations are premised on the disposal of wastes under controlled conditions in the smallest practical space and with the application of earth cover. Sites have typically been operated over periods of 10 to 20 years and many large operations have developed from small dumps which had previously required minimal planning and record keeping. Availability of lands for expansion and an ample on-site source of earth for cover often did not constrain landfilling operations. Increases in area population and industrial activity, and consolidation of smaller "local" disposal operations to larger "regional" sites significantly increased landfilling activity at these sites. Increased cost of operation and a desire to conserve available land- fill capacity has required improved and more accurate methods of monitoring site operations. Data for operations monitoring may be derived from one or more of the following methods:

i) best estimates based on visual inspections by experience site personnel;

ii) calculations based on field surveys of site topography;

iii) acquisition of aerial photography and generation of mapping derived from air photos.

Aerial photography and mapping derived from aerial photography provide data upon which to base calculations of landfill and earth fill quantities. Site age, site area, and rate of landfilling dictate a frequency of aerial photo updates. Varying from every month to every year, mapping derived and analysis of air photos provide data upon which to develop operations plans, concepts and designs for surface drainage, access roads and leachate control works. Problems associated with site operations such as erosion, ponding and revegetation may be identified in extent and degree and corrective measures taken.

The use of aerial photography provides an accurate record of landfilling operations. The site operator's performance may be monitored with time and the effectiveness of his operations assessed. Features which are readily detectible are:

i) the size and configuration of working face;
ii) spreading and compaction activities;
iii) traffic patterns and congestion at the time of photography;
iv) the effectiveness of litter control measures;
v) ponding and poor drainage;
vi) erosion;
vii) extent of earth fill stockpiles and excavations;
viii) extent of litter spread.

Analyses of site operations may be further enhanced by electronic data processing. Site final and base contours may

be digitized and compared to digitized current contours. The rate of development of the site landform and its deviation from design may be accurately assessed.

The current rapid development of computer technology, in particular in computer aided drafting and graphics in conjunction with aerial photography and mapping will in the future offer landfill managers and operators enhanced techniques for site operations, management, planning and monitoring.

Wells and Bourque (1980) investigated the use of aerial photography for landfill operations monitoring instigating programs of black and white aerial photography undertaken at the Burlington and Oakville Landfill Sites. The main objective of the program is to generate at six month intervals, site contour mapping which may be used to update site capacity. Site designs (i.e. proposed final contours and proposed excavation contours) are digitized and compared to digitized current contours. Remaining site capacity, volume of site excavations, and volume of earth stockpiles are then calculated by computer. Data between successive flights are also compared and using records of refuse weighed at the scales, estimates of landfill densities are made. The development of these techniques provides a quantitative measure of the site operations performance and monitors the site operations adherence or conformity to site designs.

4. STUDY METHODOLOGY

4.1 Selection of Sensors

Four remote sensing techniques were chosen for this present research program. These choices were based on the review of the state-of-the-art of remote sensing referred to in Chapter 2 and the evaluation of past applications described in Chapter 3 of this report. These techniques are:

1. Panchromatic archival photography
2. Colour photography
3. Colour infrared photography
4. Thermography

4.1.1 Archival Photography

Previous research has shown that the use of sequential photographs obtained from government air photo libraries provides a cost effective method of analyzing waste disposal sites.

Archives were searched and panchromatic black and white photographs, dating generally from the early 1950's to the late 1970's, were obtained. The early photography predated landfilling at each of the research sites. The sequential photographs allowed the interpreters to view the sites prior to landfill operations and then to monitor landfill development over a period of more than twenty years.

4.1.2 Photographic Sensors

a) The Camera

A Wild RC-10, single frame mapping camera was used in the survey aircraft. This camera provides individual frames in the conventional 23 cm x 23 cm format.

b) Scale

Work previously completed by the Ontario Centre for Remote Sensing (OCRS, 1978) suggested that a scale of 1:8000 would provide sufficient resolution to detect leachate conditions surrounding the landfills. Photography was flown at this scale for the first two flights, and results were applicable for the research program. It was decided, however, to decrease the scale to 1:6000 for the last two mission(s) in order to compare the effectiveness of these two scales.

c) Colour Negative Film

Kodak aerocolour negative film 2445 (Estar base) was used. This is a high speed, extremely fine grained aerial film. The spectral characteristics are shown in Figure 4. Colour prints were developed from the negatives.

This film gives a colour rendition of the ground, similar to what the human eye sees. Because of this, even untrained interpreters find it easy to relate colours on the photographs to those on the ground. In

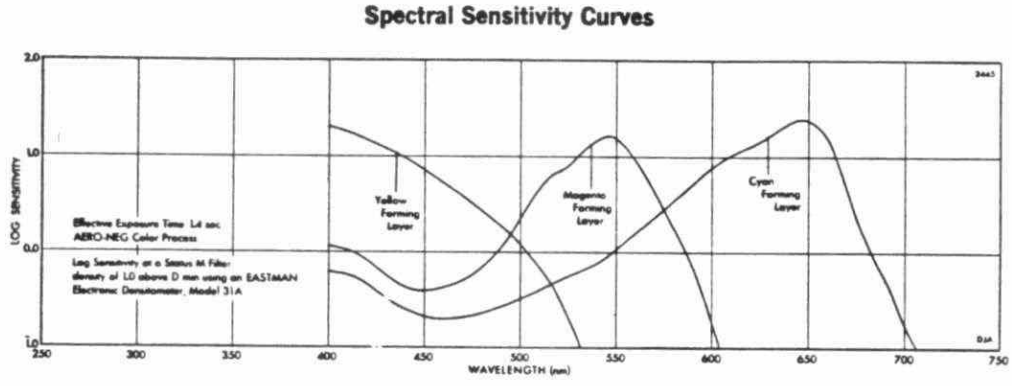


Figure 4 - Spectral sensitivity of each dye layer of Kodak 2445 colour negative film is shown. Each layer is sensitized to a different part of the spectrum and this, in effect, creates a multispectral image. (Kodak 1972).

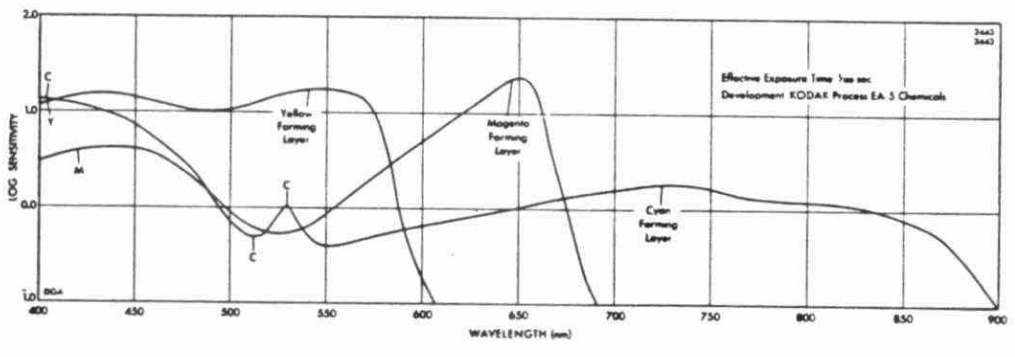


Figure 5 - Spectral sensitivity of Kodak 2443 colour infrared film is shown. Note that while the infrared layer is very broad it is not as sensitive as the blue (yellow) or green (magenta) forming layers. This means that the exposure must be correct or the non-infrared layers will dominate the picture thus reducing the value of the infrared image. (Kodak 1972).

addition, the OCRS (1978) found that the red-brown colour of some leachate was distinguishable from the green background of ground cover on normal colour film.

d) Colour Infrared Film

Kodak aerochrome infrared film 2443 (Estar base) was chosen as the second photographic data source. This is a "false colour" reversal film for applications where infrared discrimination is required. The spectral characteristics are shown in Figure 5.

While it is preferable to interpret this film in its original positive transparency form using a light table, this is not always a convenient form for interpretation. For this reason positive prints were made using colour reversal paper. These prints have somewhat less resolution and clarity than the transparencies, but they proved to be quite adequate for the purposes of our research.

Colour infrared (CIR) film which senses wave lengths extending into the infrared range, is able to detect vegetation stress - a common indication of leachate impact. In addition, the false colour tones give stronger contrast than many normal colour tones, and therefore, enhance detection of some features. Infrared wave lengths from healthy vegetation appears red on the infrared film. Any change, however, in the health of the vegetation causes a change in the infrared reflectance. As a result, the colour visible on the colour infrared film changes - to pink, yellow and grey. Dead trees appear grey.

It should also be noted that colour differences on this CIR film can cause interpretation difficulties when analyzing the infrared vegetation tones. First, different camera and light angles may cause a change in colour tone on a single print, and colour tones of the same feature on two different prints. Secondly, all healthy vegetation does not give exactly the same red tone. Slight variations may occur naturally between different species. Therefore, in detecting stress, the tone of the stressed vegetation should optimally be compared with unstressed vegetation of the same species.

4.1.3 Thermography

Research indicated that sensing in the thermal infrared portion of the electromagnetic spectrum had the ability of detecting thermal anomalies. In these cases, it has been shown (Sangrey and Philipson, 1979) that warm leachate springs can be detected against a cool ground surface. A thermal line scanner operated by Intertech Remote Sensing Limited was used.

This scanner was manufactured by Daedalus Enterprises of Ann Arbor, Michigan, U.S.A. The system employs a 1.7 milli-randian MCT (mercury-cadmium-telluride) detector sensitive to the 8-14 um wavelength range. The detector averages the incoming radiation from an instantaneous field of view on the ground of 1.7 m per 1000 m of flying altitude above the ground. The system is sensitive to radiant changes of 0.2°C with an absolute accuracy of 0.5°C.

The scanning mirror sweeps the ground at a rate of 80 scans per second. During each cycle, the mirror views two

adjustable temperature references as well as providing a field of view of 77° 20' beneath the aircraft. The output from a single scan appears as in Figure 6. All data are stored on magnetic tapes for playback at a ground processing station.

In the laboratory, the signal processing system converts the signal from the tape to a hard copy film output. Several output functions are available in processing the signal including a continuous tone analog image and a temperature level-slice image.

4.2 Selection of Candidate Landfill Sites

Six southern Ontario landfills (Figure 7) were chosen to test the remote sensing techniques under varying climatic conditions. These landfills were selected to represent a variety of hydrogeological and operating conditions, as follows. All of these landfills have leachate discharging from them at surface.

a) Cobourg

An active landfill developed on shallow glaciolacustrine sands over glacial till soils.

b) Whitby

A landfill bordering a valley environment and developed on deep sands overlying glacial till.

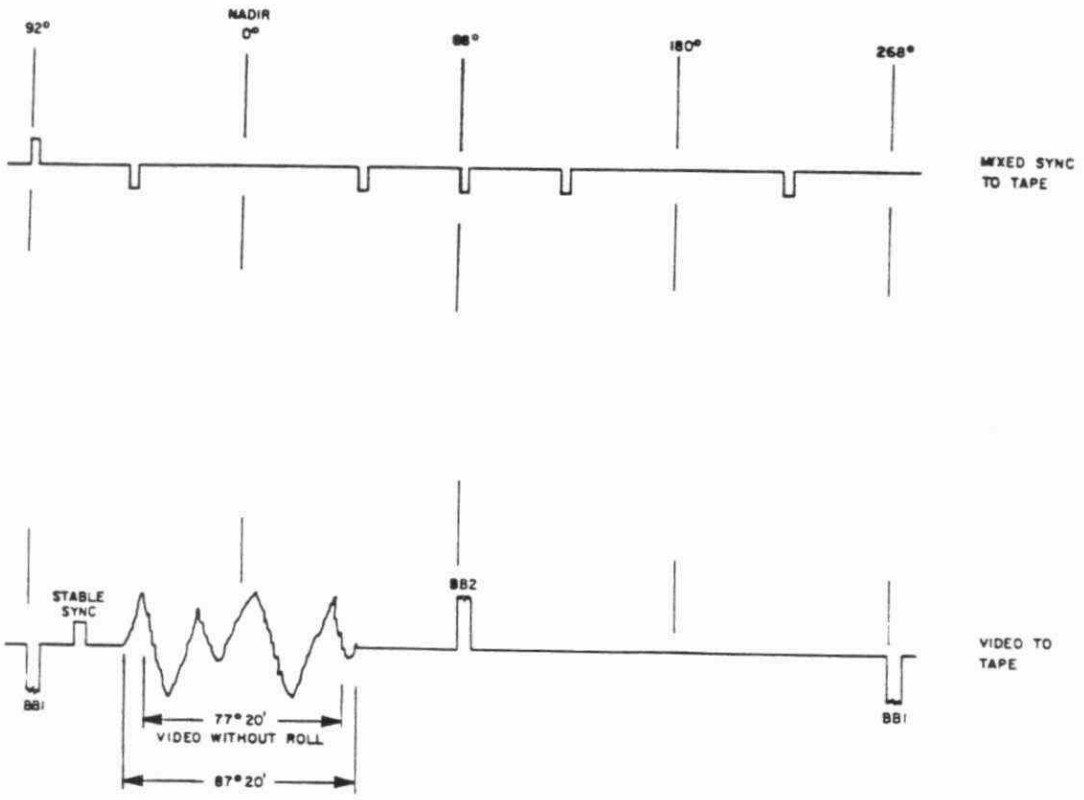
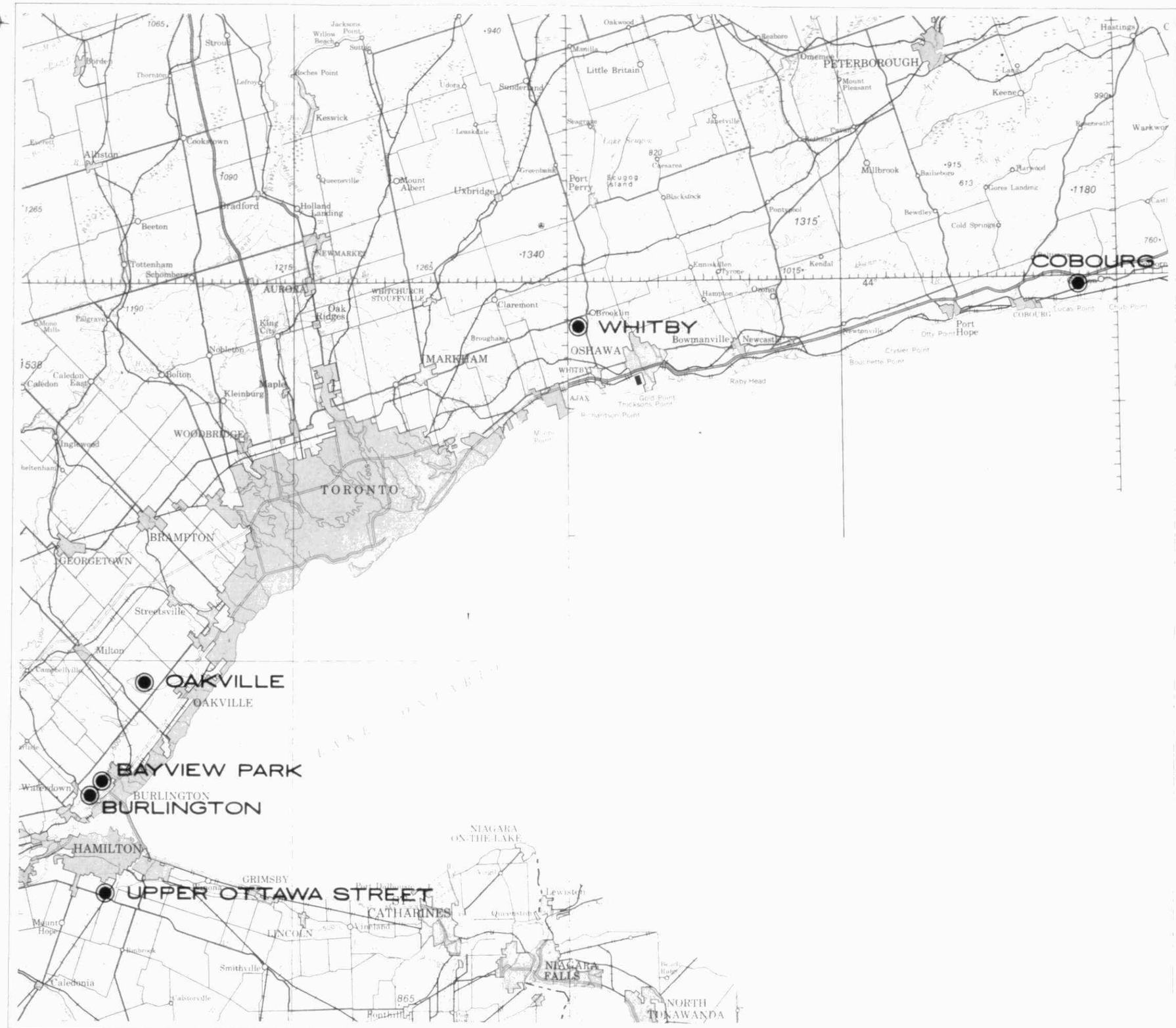


Figure 6 - The output from a single scan sequence is illustrated above. As the mirror turns, the detector records the incoming radiation from one temperature reference, the ground scene and then the other reference. As the mirror continues its circuit the mirror "looks" at the inside of the scanning unit and no information is seen. At each event in the circuit, timing marks are recorded. These timing marks are for the synchronization of the signals during playback (after Daedalus 1977).



Ministry of the Environment

Ontario

Figure 7

Landfill Site Locations

Remote Sensing Techniques & Waste Management Assessment

M. M. DILLON LIMITED

in association with

GARTNER LEE ASSOCIATES LIMITED

and

ONTARIO CENTRE FOR REMOTE SENSING

MINISTRY OF NATURAL RESOURCES

c) Oakville

An active landfill developed on a shallow glacial till plain over shale bedrock.

d) Bayview Park

This landfill has been closed for a number of years and is developed on a shale bedrock.

e) Burlington

This is an active landfill developed on shale bedrock.

f) Upper Ottawa Street

This landfill was in the process of closing during our research. There is a high mound of garbage developed on a shallow till plain which overlies dolomitic bedrock.

Details of the site conditions at each of these landfills are described in Appendices A to E. A summary of these conditions is contained in the following paragraphs.

4.2.1 Cobourg

The Cobourg landfill mound infills a stream valley incised in silty sand till. A shallow sand layer, which underlies a small part of the site, extends downstream along the valley floor. Limited amounts of leachate discharge in the sands downstream of the site and as seasonal springs around the site. A toe drain-recharge system was installed in 1976.

The 7.3 hectare site has operated since 1957 for primarily domestic wastes. Part of the site is closed and revegetated.

4.2.2 Whitby

This landfill is developed in permeable sands and gravels overlying slowly permeable silt till. Leachate from the landfill discharges away from the site, where the sand-till contact is exposed along a nearby creek valley wall. The slope is heavily treed.

The 9 hectare site began landfilling in 1971, and has received domestic solid wastes.

4.2.3 Oakville

This landfill forms a rectangular mound rising $\pm$ 10 m above the surrounding shallow silt till plain. Refuse has been placed directly on the underlying shale bedrock in most of the site. Leachate discharges in some places from the toe of the landfill mound. A toe drain-recharge well leachate collection system is being redesigned to include an expansion of the facility.

The main 24 hectare site operated from 1960 to 1980 for predominantly domestic solid wastes. A small area south of the site was landfilled between 1972 and 1978. An additional 30 acres was added to the site in 1980.

4.2.4 Bayview Park

Bayview Park landfill is located about 400 m east of the Burlington site in the same bedrock environment. Leachate discharges along the southern toe of the refuse mound. This site was added after the study had begun because it provided an example of a closed site in a bedrock setting, with no leachate control system.

The 14 hectare site operated until 1972 for predominantly domestic wastes.

4.2.5 Burlington

Burlington landfill forms a gently sloping mound in gullied shale bedrock terrain. Overburden is very shallow and consists mainly of weathered red-brown Queenston shale. Refuse was placed directly on bedrock. Leachate discharges from the landfill toe, and a toe drain collector system installed in 1980, has greatly reduced leachate seepage.

The 39 hectare landfill has operated since 1972 for solid domestic and industrial waste. Final cover has now been applied to the southern part of the site. Black and white large scale photography is used to control fill elevations during operation.

4.2.6 Upper Ottawa Street

Upper Ottawa Street landfill mound rises 20 to 30 m above a shallow till-dolomite plain. The site has also covered a creek flood plain. Refuse is placed directly on the dolomite bedrock. Leachate discharges at the landfill toe.

The 68 hectare site operated from the late 1950's to October 1980. The landfill received solid and liquid waste from the Hamilton area.

4.3 Data Collection

4.3.1 Archival Photography

Figure 8 shows the selected historical panchromatic black and white coverage obtained for each of the candidate sites. These photographs were obtained from the archives of the National Air Photo Library and the Ontario Ministry of Natural Resources. The photographs were chosen to illustrate a sequence of operations, starting from pre-landfilling to most recent (1978 photography).

4.3.2 Photographic Sensors

Aerial photography was flown by Global Remote Sensing Limited using true colour negative 2445 film and precalibrated colour infrared 2443 film. The photography format was 23 cm x 23 cm with an image scale of 1:8000 for the early March and mid-April photography and 1:6000 for the July and November photography.

FIGURE 8

SELECTED HISTORICAL COVERAGE

Site	Year	Scale	Source
Upper Ottawa Street Landfill	1954	1:15,840	OMNR*
	1965	1:17,000	NAPL*
	1972	1:15,840	OMNR
	1978	1:10,000	OMNR
Burlington Including Bayview Park	1942	1:10,000	OMNR
	1950	1:9,600	NAPL
	1954	1:15,840	OMNR
	1965	1:16,000	NAPL
	1973	1:15,840	OMNR
	1978	1:10,000	OMNR
Oakville	1954	1:15,840	OMNR
	1959	1:30,000	NAPL
	1965	1:16,000	NAPL
	1973	1:15,840	OMNR
	1978	1:10,000	OMNR
Whitby	1954	1:15,840	OMNR
	1964	1:20,000	NAPL
	1971	1:15,840	OMNR
	1978	1:10,000	OMNR
Cobourg	1954	1:15,840	OMNR
	1959	1:30,000	NAPL
	1965	1:20,000	NAPL
	1971	1:15,840	OMNR
	1978	1:10,000	OMNR

* Ontario Ministry of Natural Resources
Public Service Centre
Queen's Park
Whitney Block
Toronto, Ontario
M7A 1W3

* National Air Photo Library
Energy Mines & Resources
615 Booth Street
Ottawa, Ontario

The dates of the flights are shown on Figure 9. During 3 March 1980, a cumulus cloud cover formed over the target areas during film changing in the aircraft, and the second pass could not be exposed for three of the sites until 12 March 1980.

4.3.3 Thermography

It was originally planned that the thermography coverage was to be flown as close as possible to the dates that the photography was flown. The contractor was Intertech Remote Sensing Limited.

Specifications called for the thermography to be flown before sunrise from an average altitude of 1066 m above ground (range 1000 m to 1100 m) providing imagery with an approximate scale of 1:14000 and a line width coverage of 1812 m. This flight time was designed to give the landfills time to lose the daytime solar heat and to enhance the thermal contrast of possible leachate springs. Scale selection was based on work done by Lawrence et al (1980).

Figure 9 shows the dates on which the thermography was acquired. During the March mission an aircraft malfunction terminated the mission before completion. Appropriate weather did not occur again until winter was over. In April, difficulties with nighttime navigation resulted in the Hamilton site (Upper Ottawa Street) being partially missed. During July 1980, Ontario experienced one of its most severe forest fire seasons, and the equipment was seconded by the provincial government to help in controlling these northern Ontario fires.

FIGURE 9

DATA ACQUISITION SCHEDULE

	PHOTOGRAPHY										THERMOGRAPHY			
TIME	Mar 3	Mar 3	Mar 12	Mar 12	Apr 17	Apr 17	July 25	July 25	Nov 22	Nov 22	Mar 4	Apr 17	July	Nov 26
FILM	CN	CIR	CN	CIR	CN	CIR	CN	CIR	CN	CIR				
SCALE		1:8000			1:8000		1:6000		1:6000					
SITE:														
UPPER OTTAWA STREET		●	●		●	●	●	●	●	●	●			●
BURLINGTON (BAYVIEW PARK)		●	●		●	●	●	●	●	●	●	●		●
OAKVILLE	●	●			●	●	●	●	● (1:8000)	●	●	●		●
WHITBY	●	●			●	●	●	●	●	●		●		●
COBOURG			●	●	●	●	●	●	●	●		●		●

CN - Colour Negative
CIR- Colour Infrared

4.3.4 Field Observations

Field checks were necessary to confirm the accuracy and completeness of the 1980 remote sensing data interpretations. During visits, landfilling features were located and described. In some cases, the distinction between ground water and leachate contaminated seepage was determined using conductivity measurements. In addition, limited temperature data were acquired to assist in assessing the thermography. The initial field visits to each site occurred between May and June 1980, although individual team members had visited some sites earlier. The purpose of the initial visit was to check previous detailed mapping of leachate discharge and to familiarize the entire study team with each site.

Field visits in early August and November 1980 were timed to coincide as closely as possible with projected flight dates. During these visits, the seasonal appearance of landfill indicators was recorded. In particular, any stress in on-site and near-site vegetation was recorded in the summer.

In addition, the identity of features observed on photography was examined during field checks. However, because the 1980 data were not received until one to two months after they were flown, not all features recorded on the photography have been checked on the ground.

4.3.5 Background Data

Previous hydrogeological studies and field observations by other staff members working at the various landfill sites were collected. These were used to increase our understanding of the remote sensing data and to confirm seasonal leachate discharge conditions.

Extensive data were also collected on operations at the six landfill sites. These data, which included site records, were obtained by interviews with Regional personnel and site operators.

4.4 Data Analysis

4.4.1 Photography

All photography, including archival black and white and the 1980 colour and colour infrared, was interpreted visually, using a 4x magnification pocket stereoscope. Data were annotated directly on the paper prints. Archival data were transferred to a base map to show sequential changes in landfilling extent and drainage courses. The colour and colour infrared interpretations were located on a similar scale base map for comparison with field observations and thermography interpretations.

Some colour infrared positive transparencies were analyzed using a Bausch and Lomb Zoom Stereoscope over a light table. While it is preferable to interpret colour infrared in its original transparency format, this precludes easy annotations of the imagery without ruining it for future use. However,

comparison of interpretations derived from the paper prints and positive transparencies showed that the prints were a very acceptable data format for this project.

Detailed stereoscopic interpretation was chosen over detailed examination of single photographs because the three dimensional format allows a much greater volume of information to be obtained. Geological setting and topographic changes can be determined for a site, in addition to simple visual changes, such as vegetation gaps or drainage channel diversions. Possible impact areas can be identified from this information. Also, the probable relationship between off-site features (vegetation gaps, wetness, surface staining) and the landfill, appearing on recent photography, can be better assessed prior to the necessary field checks.

4.4.2 Thermography

Ground data from line-scanning was stored on magnetic tape for printing in the laboratory. The taped information from the scanner included two interval voltage reference sources. All of the information was fed into the "signal processor" which calibrated the ground signals by comparing them to the known voltage reference sources.

a) Analog Imagery

Line scanner imagery has been traditionallly generated in continuous tone black and white format. The processor "recognizes" the highs and lows of the input signal and modulates the printer so that relatively hot areas are printed black and relatively cold areas are printed clear on the original film. On prints made from

the original film, this temperature tone scheme is reversed: relatively cold areas appear dark; and relatively hot areas appear bright.

The analog output produces a print very similar to a black and white photograph. The continuous tone nature of the prints allows the recognition of temperature detail in the image, but does not indicate what the temperature is.

b) Level-Sliced Imagery

Level-slicing of the thermography enhances the thermal anomalies. Instead of the continuous tones from black to white that appear on the analog imagery, the tones on level-sliced imagery are divided into distinct levels representing different temperatures. Level-slice analysis within the processor involves three basic steps:

1. Two reference levels are created which define the calibration range (outputs corresponding to voltage levels from the two reference sources).

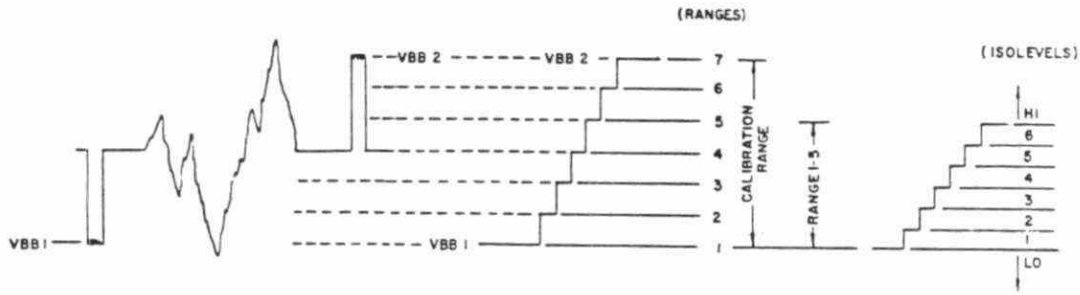
2. A processing range is selected based upon the position of the ground scene within the total calibration range and the portion of that signal which is to be emphasized. The processing range may be as small as one-sixth of the calibration range or as large as the entire calibration range.

3. The processing range is subdivided into six iso-levels which provide grey level outputs to the film printing unit.

Figure 10 shows a signal from the scanner which has calibrated thermal reference sources producing voltages V_{BB1} and V_{BB2}. Electronic sample-hold circuits extract V_{BB1} V_{BB2} and from the input signal for use as calibration reference voltages. The difference between V_{BB1} and V_{BB2} represents the full calibration range of the instrument. The voltages V_{BB1} and V_{BB2} are applied to opposite ends of a precision voltage divider to create six equal voltage increments within the full calibration range. Ranges are then defined, as in Figure 10, by numbers representing the divisions between voltage increments; such as range 1-2, range 2-5, or the full calibration range 1-7.

Once an appropriate range is selected, the processor automatically subdivides the signal into six equal voltage increments which correspond to the isolevels shown on Figure 10. Whenever the ground scene level is within a given isolevel increment, an output voltage is supplied to the film printer unit to give an appropriate grey level on the film. Signals above and below the selected range form the darkest and lightest levels on film to give 8-level-sliced processing.

Again, using Figure 10 as an example, examination of a "master set" of eight grey levels might lead to a desire for greater processing resolution within that range. This can be accomplished by making additional "subset" passes. If the scanner operator adjusts the reference source temperatures so that the total calibration range 1-7 was utilized by the ground scene in Figure 10, thirty-six calibrated levels can be achieved. System noise sometimes limits the practical number of sublevels to something less than thirty-six divisions and the smallest temperature level to 0.25°C.



					6-7
				5-6	5-7
			4-5	4-6	4-7
		3-4	3-5	3-6	3-7
	2-3	2-4	2-5	2-6	2-7
1-2	1-3	1-4	1-5	1-6	1-7

Figure 10 - The calibration range of the input signal is determined by the two reference temperatures BB_1 and BB_2 . The processor automatically divides the input range in Hi-Lo and six equal levels in between. The master range 1-7 provides the largest span between levels because the 1-7 ranges uses BB_1 and BB_2 as the upper and lower end of the level-slice. From the master range any combination of sub-ranges can also be broken into the Hi-6-Lo isolevel product. Thirty-six possible combinations are available and depending on the temperature spread between BB_1 and BB_2 the smallest level possible is 0.25°C. (Daedalus 1977).

Level-sliced data actually produce a map of temperature variations. At present, knowing where areas of similar temperature are around a landfill is more important than knowing the actual temperature range of each unit. More research is needed to determine the significance of knowing true temperature as opposed to knowing that one area is relatively warmer or cooler than another.

5. STUDY RESULTS

5.1 General Comments

This research study has involved the evaluation of four remote sensing techniques applied to six different southern Ontario landfills exposed during four seasons of the year. This has produced a large amount of research information.

Details of the data collected at each of the six landfill sites are presented in Volume 2 of this report. A synthesis of these results is presented in this chapter and organized on a sensor basis - i.e. archival photography, colour photography, colour infrared photography and finally thermography.

The reader is referred to Volume 2 of the report for a detailed description of the results on a site by site basis.

5.2 Archival Photography

5.2.1 Diagnostic Elements

Sequential aerial photographs, taken over a time span of a number of years, are termed "archival photography". These archival photographs are very useful in:

i) locating existing and closed landfill sites; and

ii) assessing the probable location of leachate discharge zones.

Figure 11, which is a tabular summary of the study results, shows that the archival photography was used successfully at every site in both locating the sites and predicting leachate seepage zones.

The photographs are interpreted to determine the geological setting prior to landfilling and the sequential development of the landfill. Changes in the landscape related to landfill activity are plotted and compared to one another for the different years of landfill operation.

Three features visible on the archival photography generally locate the landfill area:

i) development of a refuse mound;
ii) diversion of the original surface water drainage; and
iii) the presence of disturbed land surfaces.

Figure 12a illustrates the effect of Bayview Park landfill on the local topography and surface drainage.

While the presence of a refuse mound, which is often clearly a landform anomaly, and diverted drainage are strong indicators of landfilling, disturbed land surfaces are not so conclusive. As a result, additional evidence of landfilling must be obtained, such as subsequent photographic data showing filling, municipal records or field examination. For example, the disturbed land surface south of the main Oakville site is the only indication that landfilling occurred here between 1972 and 1978 (Figure 12b). However, this had to be confirmed by municipal records. Very often disturbance may be due to other activities around a site,

FIGURE 11

SUMMARY OF STUDY RESULTS

IMAGERY	COBOURG				WHITBY			OAKVILLE					BAYVIEW PARK					BURLINGTON				UPPER OTTAWA STREET			
ARCHIVAL																									
Landfill Extent	Y				Y			Y					Y					Y				Y			
Leachate Discharge	Y				Y			Y					Y					Y				Y			
1980 PHOTOGRAPHY																									
INDICATOR	Staining	Vegetation		Wetness	Staining	Veg Stress	Snow Gap	Staining	Wetness	Vegetation		Gullies	Staining	Wetness	Vegetation		Snow Gap	Staining	Wetness	Vegetation		Staining	Wetness	Snow Gap	Veg Gap
		Gap	Stress							Stress	Gap				Stress	Gap				Stress	Gap				
Colour																									
Late Winter	N	N	N	I	Y	N	I	I	I	N	N	Y	I	N	N	N	Y	I	N	N	N	N	I	N	N
Spring	Y	N	N	N	I	N	N	Y	I	N	N	N	N	Y	N	N	N	N	I	N	N	Y	Y	N	N
Summer	Y	Y	Y	N	N	Y	N	Y	I	Y	I	N	N	N	I	I	N	N	Y	I	Y	Y	Y	N	I
Autumn	N	N	I	N	I	N	N	Y	I	N	N	N	I	N	I	N	N	N	N	N	N	I	I	N	N
Colour Infrared																									
Late Winter	N	N	N	I	N	N	N	N	I	N	N	I	N	N	N	N	I	N	N	N	N	N	I	Y	N
Spring	I	N	N	N	N	N	N	Y	I	I	N	N	N	Y	N	N	N	N	Y	N	N	I	Y	N	N
Summer	Y	Y	Y	I	Y	Y	N	Y	N	Y	I	N	N	N	Y	I	N	N	Y	I	Y	I	Y	N	I
Autumn	N	N	I	N	N	I	N	Y	I	N	N	N	N	I	I	N	N	N	N	N	N	N	I	N	I
THERMOGRAPHY																									
FEATURES	Springs		Ponding		Springs		Ponding	Springs		Ponding			Springs		Ponding			Springs		Ponding		Springs		Ponding	
Late Winter	–		–		–		–	Y		Y			Y		N			Y		I		Y		Y	
Spring	Y		I		I		I	Y		Y			I		N			Y		Y		–		–	
Autumn	Y		I		I		N	Y		Y			N		N			Y		I		Y		Y	

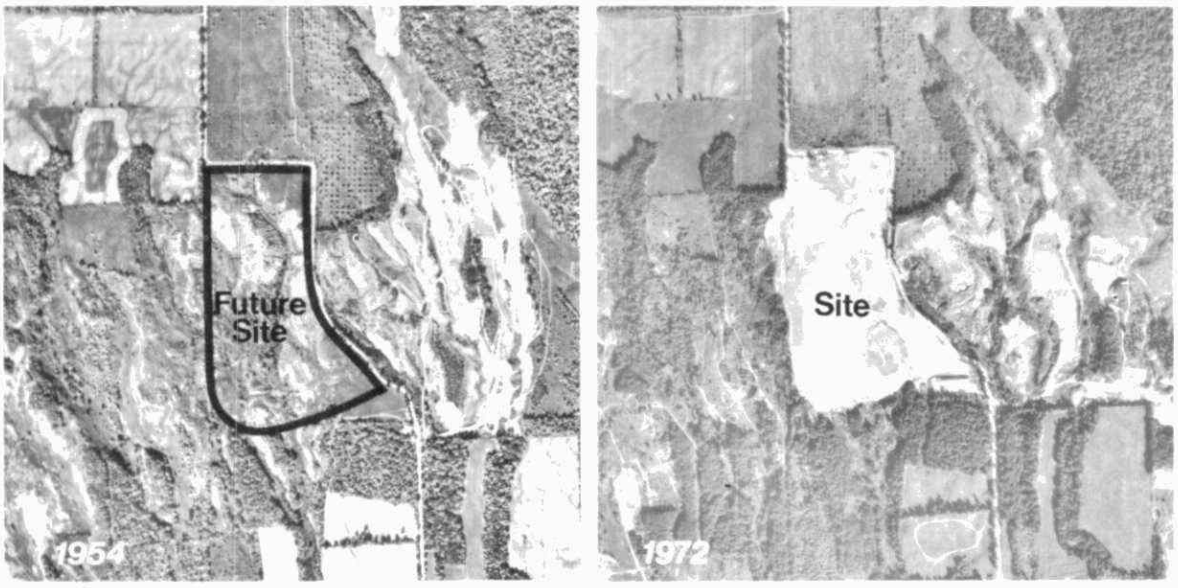
Y = At least one feature clearly identified I = Feature indistinct or inconclusive N = Not identified NOTE = This is not a weighting system

such as construction, or gravel extraction. In such cases, the normal surface activities may mask small areas of disposal activity.

The general location of leachate discharge zones can often be predicted by comparing pre-landfill with recent photographs. A hydrogeologist can predict the likelihood of leachate mounding within the refuse, and where such leachate might migrate, by properly interpreting the archival photographs. While such predictions are not conclusive they can guide field checking and distinguish potentially serious situations.

For example, the refuse mound at Bayview Park (Figure 12a) developed along several southward draining bedrock gullies. Although leachate will also migrate into the bedrock, a mound may develop in the refuse. Leachate movement will follow the original surface drainage, discharging along the southerly face of the landfill, particularly along the former drainage channels. A different situation occurs at Whitby landfill, where the site is developed in permeable sands over glacial till. Interpretation of the archival photography identifies the geological setting and the ground water seepage occurring along an adjacent stream valley. While a leachate mound is unlikely to develop in this environment, because of the permeable nature of the sands, contaminants will migrate through these permeable sands and discharge along the valley wall. Field checking identifies that the actual leachate seepage corresponds with the zones of probable seepage located using archival photography.

The sequential nature of the photography, where operations are actually monitored during the years, can also be used in identifying possible leachate discharge. At the Oakville landfill, interpretation of the archival photography gave



i *ii*

(a) Bayview Park Landfill before (1954) and after (1972) landfilling (scale 1:15840); smooth refuse mound in rugged bedrock topography indentifies landfill location and diverts original drainage.

i *ii*

(b) Oakville Landfill during operation: disturbed surface appears near main landfill in 1978 (note change at 1 from 1972 to 1978); drainage from landfill in 1972 visible at 2: (scale 1:15840 in 1972; 1:10000 in 1978).

Figure 12 - Archival Photography

designers an explanation for a very active seepage area along the landfill toe. Interpretation of the 1972 photography (Figure 12b) showed that the lower part of an original drainage channel had been improved to drain the working landfill face. Although this drain was subsequently filled, it still formed a natural channel to collect leachate and allow it to migrate out of the face of the mound.

While archival photography, however, can be interpreted by experienced personnel to identify potential leachate discharge zones and field investigation check points, it does not gauge the current effectiveness of toe drains nor current impacts of leachate discharge. Nor is it possible to predict the location of perched leachate mounds, which may cause local but vigorous leachate seepage. Such information must be obtained by field examination. It must be noted though, that all the remote sensing techniques studied require ground truthing to fully assess conditions.

5.2.2 Sensor Evaluation

Archival photography is a versatile and practical tool when used to predict the extent of landfilling and the location of possible leachate discharge areas at surface.

At most of the landfill sites, a simple comparison of the interpretations of pre-landfilling photography with that of 1978 photography provides sufficient information to predict the landfilling boundaries and probable leachate springs. Still, comparisons with photographs taken during the intervening years provided even more information on the event of landfilling, sequence of operations and the diversion of drainage. For example, if urbanization had obscured earlier landfills, or where the original landfill did not

significantly alter topography or surface drainage, the intervening sequential photography becomes critical. A progressive case history of the site can be developed from the photography, to identify the period of landfilling activity plus any remedial works that may have occurred upon closure. Furthermore, the archival photography can provide a definite time period for investigators to concentrate their research when exploring other data sources, such as government records or public recollection, to confirm the landfill activity.

5.3 Colour Photography

5.3.1 General Comments

Analysis of the 1980 colour photography concentrated on the identification of current landfill impacts, primarily leachate discharge, in the different seasons of the year. In general, an interpretation of this seasonal colour photography proved successful in identifying leachate springs. However, a number of springs were not discernible on the colour prints, and the effectiveness of the interpretation varied not only with the season of photography, but also with the site studied. As a result, it was imperative to field check for accuracy and completeness of the interpretations.

The extent of refuse and the probable location of leachate discharge also can be approximated from interpretation of the site topography and geological setting on the colour imagery.

5.3.2 Leachate Indicators

It is very difficult to see the actual discharge of leachate on the colour aerial photographs even at a scale of 1:6000. Instead, the interpreter detects such a condition indirectly by assessing diagnostic clues. Seepage zones are often too small to see or they are obscured by vegetation.

The characteristics of these diagnostic indicators varied at each site. The features were often indistinct or inconclusive in identifying leachate discharge (Figure 11). They might also vary with the season, being very clear at one time and then deteriorating or disappearing from the photographs as conditions changed through the year.

Even so, the diagnostic features can be grouped into several categories, with each category having similar characteristics based on the type of impact created by the leachate discharge.

a) Staining

Staining of surface material - snow, grass or soil - by leachate is a visible indicator on the colour photography. Typically, it appears as a red-brown tone, ranging from a very dark to a faint colour anomaly on the ground surface. Staining was clearest on the spring and summer imagery. Several examples of surface staining are illustrated on Figures 13 and 14.

Staining is a good indicator of leachate discharge when it occurs as a distinct feature on the landfill face (Figure 13, #3 Oakville), or when the staining near the landfill has a "stream-like" form (Figure 14, #1 Cobourg). At Oakville, the leachate stain is also

associated with dead vegetation. This is illustrated in Figure 15(a). This combination of features increases the probability that the stain, which appeared between the April and July flights, is leachate discharge.

Unfortunately, the majority of surface stainings observed on the colour photographs are not conclusive indicators of leachate discharge. The reasons for this are two-fold. First, the red-brown staining is frequently indistinct or very faint on the photographs. The leachate colouration often contrasts poorly with the background soil or forest floor (Figure 13, #4; Figure 15(b)); even leachate staining of snow appears as only a faint discolouring at the study sites. Secondly, the red-brown tone is not a unique colour in the landscape, associated only with leachate staining. At several sites, natural materials in the environment have the same colour. For example, at Burlington surface runoff causes the same red-brown staining of snow as leachate discharge. At Whitby, red-brown colours are observed along the leachate discharge zone in spring; however, the same or very similar tones are observed scattered throughout the stream valley, obviously caused by non-leachate induced conditions.

Furthermore, not all leachate has this red-brown colouration - both black and colourless leachate discharge was observed at several sites. In the case of clear discharge, non-visual features, such as odour or chemical composition, which can only be determined in the field, are neccessary for identification.

Oakville Landfill (July 25, 1980; Scale 1:6000; Colour)

1. Natural vegetation gap.
2. Leachate seepage and dead grass.
3. Leachate seepage-staining, halo of dead grass, and dead cattails in ditch (See Figure 15a).
4. Red-brown leachate staining (faint)
5. Ponding of surface run-off; possible leachate contamination but red-brown tone relates to soil cover.
6. Active face.
7 Incomplete revegetation of closed fill area.
8. Leachate recharge well.
9. Leachate seep - not visible on photograph (see Figure 15b).

Figure 13 - Colour Photography

Cobourg Landfill (April 17, 1980; Scale 1:8000; Colour)

1. Leachate outbreak, red-brown staining.
2. Overflow from recharge trench staining grass.
3. Leachate seeping from active face.
4. Linear vegetation gap; minor seepage area.
5. Gap in tree cover; not currently related to landfill.

Figure 14 - Colour Photography

(a) Leachate staining on landfill face; leachate has killed grass on landfill and cattails in perimeter ditch. (Oakville Landfill)

(b) Typical leachate seep at Oakville landfill; note the small size and lack of contrast with background soil.

Figure 15 - Leachate Discharge

b) Wetness

Areas of wet soil and surface ponding are always suspect as possible leachate discharge locations on and near landfills. Such indicators are more conclusive when:

i) they occur on the landfill face;

ii) they persist through dry periods; and

iii) another discharge indicator is associated with the wetness (i.e., staining).

Soil wetness is generally not easily detected on the colour photography. Furthermore, at most sites there is no way to distinguish between natural surface runoff ponding and leachate - contaminated ponding (e.g. Figure 13, #5). However, surface wetness can be an important indicator when tied into other features (location, colour). For example, at Upper Ottawa Street, dark coloured leachate has collected in a pool and along a perimeter runoff ditch. In this case, the "wetness" or ponding is the only indicator on the colour photography of the seepage from the landfill toe.

c) Vegetation Effects

The impact of leachate discharge on vegetation could be detected on the colour photography, although this was more clearly detected on the colour infrared film. Best observations were made in summer, when areas of dead trees or dead grass (e.g. Figure 15, #2, #3) could be distinguished. At some sites, the more lush growth of grass cover due to wetness from leachate seepage could

also be distinguished. But more subtle vegetation stress and very small stressed areas were not visible on the colour photography.

The existence of stress close to the landfill, however, is an insufficient indicator of leachate discharge, as will be noted in the discussion of colour infrared results.

Gaps in landfill vegetation cover are quite clear on the summer colour photography. Most of the gaps occur at the landfill toe. While some gaps are caused by leachate kills, most are due to incomplete natural re-vegetation of the site. And generally, unless there is distinct leachate staining at the gap, it is not possible to distinguish on the colour photography between the natural vegetation gaps and the leachate-caused gaps.

d) Snow Gaps

The high salinity and warmth of leachate can cause snow cover to melt around the discharge area. Snow gaps were observed at the toe of several landfills in March, identifying leachate discharge. The most distincitve gap had a stream-like form, extending along the lower landfill slope.

However, gaps in snow cover are not unique to leachate discharge. Any turbulent flow in a stream may prevent snow cover from remaining, and this effect was observed at several sites. Furthermore, the effectiveness of snow gaps is highly weather dependent. For example, gaps in snow cover at the Upper Ottawa Street site

identified leachate discharge on the colour infrared film, but snowfalls during the following week had covered these areas when the colour photography was flown nine days later.

None of these diagnostic features is a unique indicator of leachate discharge. They are often small, indistinct and inconclusive when observed on the colour photographs. The actual identification depends primarily upon the skill of the interpreter and the deductive convergence of evidence. As an example, not only the existence of a feature, but its location with respect to the landfill, its form, colour and possible cause are all factors to be evaluated in relation to the experience and knowledge of the interpreter. Since many features can occur naturally, it is necessary to determine whether leachate discharge could, hydrogeologically, be discharging at any particular location.

Furthermore, the colour photography does not allow distinction, in many cases, between natural and leachate-caused features. Hence, mere proximity of a feature to the landfill is not conclusive identification of leachate discharge, it may result from natural or other man-made causes. Nor, obversely, does the lack of any photographic indicators at a site confirm that leachate discharge is not occurring. As a result, once indicators are located on the photography, they must be confirmed in the field as locations of leachate discharge.

5.3.3 Factors Affecting Detection

Three factors affected the ability of the interpreter to identify leachate related conditions. These factors are:

a) the conditions of leachate discharge
b) general site conditions
c) seasonal conditions

Because of one or a combination of these factors, leachate detection on the colour photographs was generally incomplete at each of the research sites. Field checks showed that some seepage was consistently missed, while other smaller seeps were detected because of their location and contrast with the background.

a) Leachate Discharge

The most accurate and conclusive photographic detection occurred when leachate discharged at surface, creating a distinct visual impact. However, in the majority of cases, leachate discharge visually affects only a small area close to the discharge point. Even the most vigorous leachate springs are small in size and their visual impact may not be proportional to their discharge. Often the discharge occurs amongst the scrub vegetation at the landfill toe, and the impact area is obscurred by overhanging vegetation (Figure 16(a)). Furthermore, although leachate typically has a red-brown colour, black and colourless discharges are observed (Figure 16(b). As a result, perched leachate seeps occurring high on the landfill face, may be detected against the bare landfill slopes while other possibly more vigorous discharge is obscured by vegetation near the landfill toe.

Leachate seeping on Bayview Park Landfill. The small seep has killed vegetation only along its flow path. Much of the impact is obscured by adjacent grass.

Figure 16(a) - Leachate Seepage

Leachate spring at Bayview Landfill. This vigorous toe spring is colourless and creates a small visual impact when detected from the air. The staining is probably precipitate from the leachate.

Figure 16(b) - Leachate Seepage

b) Site Conditions

Five of the study sites were active landfills during the study period. As a result, surface conditions are constantly changing as refuse is added and soil cover regraded. This inhibits the visual development of seepage zones on the landfill face. At two sites, seepage was actually covered by final soil cover and obscured on the November photographs.

c) Seasonal Conditions

There is a fairly clear seasonality to the colour photography by results - fewer observations in late winter and autumn than in spring or summer. Some of this is due to variation in leachate production, although many seeps were as active in November as in April or May.

Background conditions also change with seasons. Obviously, snow staining and gaps can only occur in winter; however, snow can also cover discharge areas. Similarly, vegetation impacts are generally clearest in summer. But again, vegetation cover may also obscure seeps at this season.

5.3.4 Sensor Evaluation

The effectiveness of the colour photography in monitoring leachate discharge varied considerably between the sites. At some landfills, all leachate discharge was located when the results from the four seasons were combined. At other sites,

certain discharge areas were consistently missed by the photography. In several cases, discharge was observed in only one season at a given location.

Generally, the best results were obtained on the spring and summer colour photography (Figure 17). Looking at Figure 11, it is apparent that the highest number of indicator observations occurred in summer. This reflects the vegetation impacts which could be detected in this season. However, actual detection of discharge areas did not vary significantly between the spring and summer and at some sites, the features were more conclusive in spring.

The change in scale from 1:8000 to 1:6000 did not appear to significantly increase the ability to detect leachate discharge on the colour photographs. Considering the very small size of many features, it is preferable to use the larger scale (1:6000) when possible.

5.4 Colour Infrared Photography

5.4.1 General Comments

The major advantage of the colour infrared is its ability to detect stress in vegetation and the enhancement of surface drainage effects on the photographs. As with the colour photography, it was not possible to actually see the discharge of leachate. Rather, a number of indicators were interpreted that suggested leachate conditions. These indicators are discussed in the following sections.

FIGURE 17

STUDY SENSOR EVALUATION

SENSOR \ SITE	COBOURG	WHITBY	OAKVILLE	BAYVIEW PARK	BURLINGTON	UPPER OTTAWA STREET
ARCHIVAL	●	●	●	●	●	●
1980 COLOUR PHOTOGRAPHY						
L.W.						
Spring	●		●	●		●
Summer		●			●	
Autumn						
1980 COLOUR INFRARED PHOTOGRAPHY						
L.W.						
Spring				●		
Summer	●	●			●	
Autumn						
1980 THERMOGRAPHY						
L.W.	–	–	●	●	●	●
Spring	●	●				–
Summer	–	–	–	–	–	–
Autumn	●					

Note: 1. ● Indicates Optimum Sensors for Detecting Landfill Impacts
2. L.W. Late Winter
3. – No Imagery Available

5.4.2 Leachate Indicators

The major categories of leachate indicators observed on the colour infrared (CIR) film are the same as those observed on the colour film. These indicators are often indistinct or inconclusive of leachate discharge. In addition, there are variations in features between sites and between seasons at the same sites. As an example, no diagnostic indicators were observed at several landfills in November and March (Figure 11).

The characteristics of the diagnostic features, their general appearance on the CIR film and their strength as an indicator of leachate discharge, are outlined below.

a) Vegetation Effects

Because of the ability to sense vegetation stress, vegetation effects had the potential to be more significant as leachate discharge indicators on the colour infrared film than on the colour. The best observation period is in summer, when vegetation growth is at its maximum.

Leachate discharge can cause both positive and negative vegetation stress. Positive stress occurs when vegetation growth (usually annual vegetation cover) is enhanced by the moisture of a leachate seep. It appears as more vigorous vegetation growth, either in early spring or summer, or as persistent growth in late autumn. A good example of this occurs at Bayview Park landfill, where a line of healthy vegetation (cattails) appears on the landfill face in summer. The red vegetation tone contrasts with the stressed surrounding ground cover on the CIR film and clearly locates a

leachate seepage zone and spring. This was not clear on the colour photographs (Appendix D). Negative stress occurs when vegetation is damaged by leachate discharge. This may cause outright death of vegetation, killing ground cover within a few weeks or tree cover over a period of years, or only partial damage to vegetation. Figures 18 and 19 illustrate various vegetation stress at Whitby and Cobourg landfills during the summer.

Because leachate is discharging along the wooded valley wall, summer CIR photography was particularly effective in locating the main leachate spring zone at Whitby (Figure 18). The line of discharge is indicated by the dead cedars (grey) which contrast with surrounding healthy (red) trees. The general trend of leachate movement from the discharge zone is indicated by the stressed vegetation extending towards Lynde Creek. Stressed ground cover (pink tone) observed on the flood plain, between the landfill and Lynde Creek, may also indicate leachate impact.

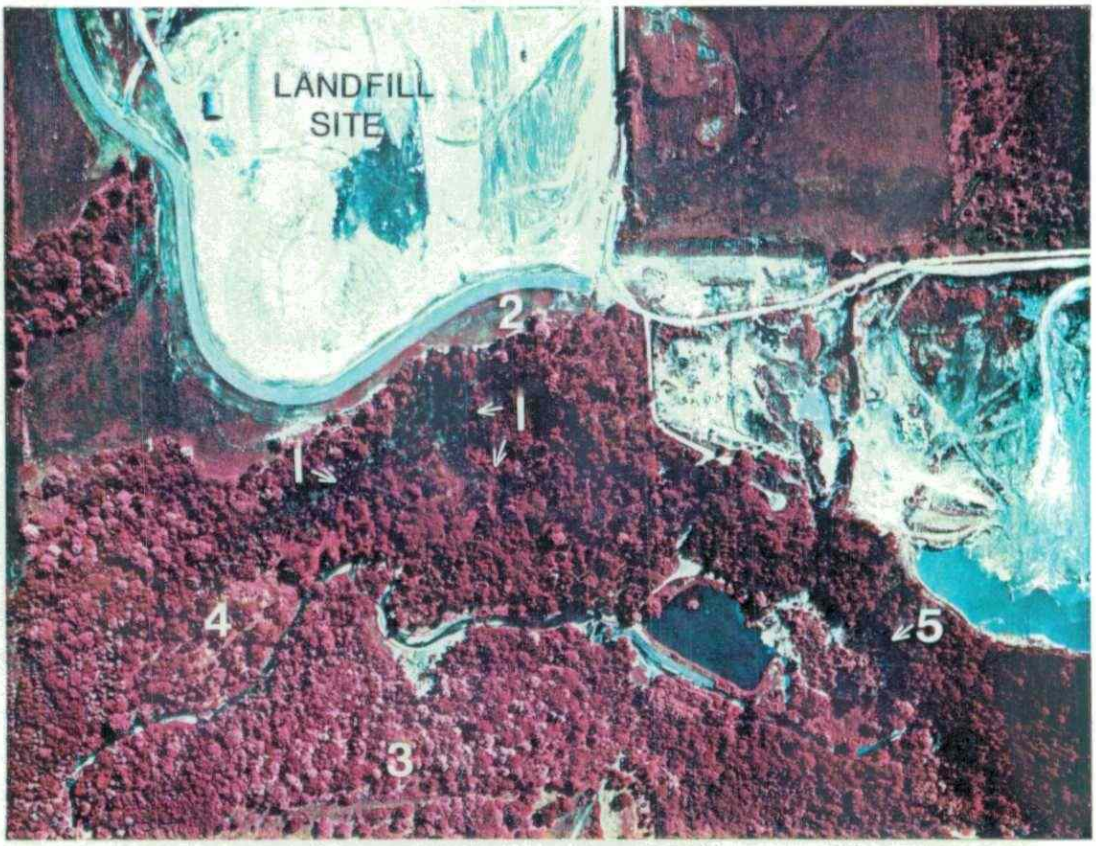
However, Figure 18 also illustrates that all negative stress close to a site is not necessarily related to the site. For instance, the clump of dead trees downstream of the pond (Figure 18, #5) were killed by siltation from runoff; the scattered stress in trees on the west bank of Lynde Creek (opposite the landfill) occurs naturally. While the lack of connection between the landfill and these features can be proved in the field, it can also be determined by stereoscopic interpretation of the geological setting from the aerial photographs.

At Cobourg, positive vegetation stress is apparent in grass cover around an overflow of leachate from the recharge trench (Figure 19, #1). Negatively stressed

vegetation occurs downstream of the landfill, along the creek valley. The stressed vegetation adjacent to the site (Figure 19, #4), is an area of leachate discharge. However, the dead trees near this area (Figure 19, #7) are not related to current leachate discharge. While these trees could have been affected by earlier discharge, prior to the toe drain installation, there is no evidence to support this.

Several gaps in vegetation are visible on the Cobourg site (white toned bare soil; Figure 19). While some gaps are associated with leachate discharge, many are due to erosion or incomplete initial re-vegetation - the difference cannot be distinguished on the photographs. The inability of the CIR to distinguish between natural and leachate caused vegetation gaps, unless there is another leachate indicator visible, is typical of the study sites. This is similar to the colour photography.

There are a number of difficulties associated with the interpretation of vegetation stress on the infrared photographs. Since annual plants can adapt to leachate, most negative stress is observed in trees. However, unless the leachate has caused a change in the top of the tree it may be undetected - healthy vegetation on upper branches will obscure stressed vegetation on lower branches or on the ground surface. In addition, there is no way to determine if stress is caused by the landfill or by other environmental features, unless there is clear supporting evidence of leachate discharge other than just proximity to the landfill. As a result, lack of visible vegetation stress does not signify



1. Major leachate zone; dead trees along slope and on flood plain towards Lynde Creek.
2. Stressed tree.
3. Stressed trees; stress not related to landfill.
4. Stressed ground cover.
5. Dead trees not related to landfill.

Figure 18 - Whitby Landfill

(July 25, 1980; Scale 1:6000; colour infrared)

1. Positive stress adjacent to leachate overflow.
2. Yellow-green staining represents red-brown leachate staining.
3. Cut-over gap, with dead cedar branches (yellow-green)
4. Stress (orangey-red) and dead trees mark leachate seepage.
5. Soil wetness (dark tone) may indicate seepage or run-off ponding.
6. Yellow-green staining represents remnant of red-brown leachate seepage.
7. Dead trees; not related to current landfill practice.

Figure 19 - Cobourg Landfill

(July 25, 1980 1:6000, Colour Infrared)

absence of leachate discharge, nor does detection of vegetation stress confirm leachate discharge. Any such conclusions require field checking.

Colour infrared film was superior to colour in identifying positive and negative stress (Figure 11). This is due to greater tonal contrasts and the ability to detect changes in infrared reflectance of vegetation on the CIR film.

b) Wetness

As stated earlier, any wetness on the landfill surface or adjacent to the site is suspect as an area of leachate discharge. Areas of soil wetness or surface ponding are most conclusive when:

i) they occur on the landfill face;

ii) they persist through dry periods; or

iii) another discharge indicator is associated with the feature (e.g. vegetation kill).

Areas of soil wetness are more clearly detected as a dark tone on the colour infrared than on the colour photographs because of the sensitivity of the CIR film. However, surface ponding is often not as clear since the sediment laden waters did not contrast well with the soil background.

Unfortunately, these wetness features are not unique to leachate discharge - similar features are created by melting snow or ponded surface runoff. Furthermore, while the location of wet soil areas adjacent to the

landfill face (e.g. Figure 19, #5) is a strong indication of probable leachate discharge, there is no means to conclusively identify the wetness as leachate or leachate contaminated water without field checking.

c) Staining

Red-brown staining by leachate of soil and grass is poorly detected by the colour infrared photographs. The red-brown staining appears as a blue-green tone on most of the CIR prints. This tone is very hard to distinguish against the usually false colour blue tones of the soil or grass cover in late winter, spring and autumn. As a result, the area of staining visible on the CIR photography, if it is visible at all, is much less than on the colour photographs at these seasons.

In summer, however, some of the red-brown staining appears as a yellow-green tone (Figure 19, #2, #6). This contrasts well with the background, and in some cases, the discharge is more easily detected on the summer colour infrared than on the summer colour film.

Unfortunately, the staining tones are not unique indicators of leachate. As observed on the colour photographs, similar colours occur naturally in the environment. For example, looking at the Cobourg landfill (Figure 19), one can see yellow-green tones at the overflow from the leachate recharge trench (#2) and downstream of the site in an opening in the tree cover (#3). While the staining at 2 is due to leachate the colour at 3 is the red-brown tone of dead cedar boughs, which cover this cut-over area of trees.

d) Snow Gaps

Gaps in the snow cover around the landfill sites were also observed on the March colour infrared photographs. These gaps were no more clear or conclusive than the same gaps observed on the colour photographs. And the same problems of weather dependency and the inability to usually distinguish natural and leachate-caused gaps in snow cover occur with CIR imagery as occur with colour. Any tentative identification relies on the location of the gap and other features associated with any observed snow gap.

Leachate indicators or diagnostic features on the colour infrared photography have many of the same problems or restrictions as the features observed on the colour photography. While the false colour makes some features more distinct on this imagery most indicators are generally small and inconclusive in identifying leachate discharge. Much of the actual identification depends upon the skill of the interpreter and the ability to draw together various pieces of supportive evidence at a site, such as location of a feature, its possible hydrogeological relation to a site and presence of other man-made and natural factors. Simple recognition of a particular tone or area of vegetation stress is inadequate.

Furthermore, it is impossible in many cases to distinguish on the CIR photography between natural and leachate-caused features. The most definite identification occurs when several features combine at one location. Single indicators,

however, can still be useful for guiding field checks. Also, if leachate is known to have discharged at a given location before, the single indicator can identify that discharge is continuing to occur.

Unfortunately, leachate discharge is not always detected by the photography. Therefore, just as observation of a leachate indicator close to the landfill on the CIR imagery is insufficient to conclusively identify leachate discharge at a site, so the absence of photographic indicators around a site is insufficient to confirm that no leachate discharge is occurring.

5.4.3 Factors Affecting Detection

The three main factors which affect the ability of the interpreter to identify leachate related conditions on the colour photography also apply in interpretation of colour infrared imagery:

a) the conditions of leachate discharge
b) the general site conditions
c) the seasonal conditions

Because of one or a combination of these factors, leachate detection on the CIR photographs was generally incomplete at each research landfill site. Detection was more erratic on the colour infrared than on the colour imagery, except during the summer, and field checks show that a higher proportion of the leachate seepage was not observed on the imagery.

a) Leachate Discharge Conditions

Much of the leachate discharge observed at the study sites occurs in vegetated areas near the landfill toe or just off-site. When this causes significant vegetation stress, the discharge zone can be detected by the colour infrared imagery (e.g. Whitby landfill). More commonly, leachate does not create a major visual impact on the vegetation at the study sites, because either there is no visual impact at all or it is obscured by adjacent vegetation (Figure 16). In these cases, the colour infrared is no more successful in identifying leachate discharge than the colour photography.

b) Site Conditions

The active site conditions at the study landfills affected leachate discharge detection on the colour infrared film. The constant surface changes prevented visual development of leachate seepage on the landfill face. As a result, soil wetness, which potentially would have been a clear indicator on the CIR film, was not a well developed feature on the landfills. The activity also obscured known seepage areas, particularly in November at the Oakville and Burlington sites. In addition, the bare soil cover at the landfills provided a very poor background for detecting any staining - a feature already hard to detect on most CIR imagery.

The lack of on-site vegetation at most study landfills restricted the effectiveness of CIR in summer. Note that positive stress in ground cover was an indicator of discharge at the Bayview Park and Cobourg landfills - both closed sites with at least partial revegetation.

Conversely, summer colour infrared imagery was much less effective in detecting leachate discharge at Upper Ottawa Street - a site with only patchy natural vegetation along the landfill toe.

Vegetation conditions around the site can influence detection on the CIR photographs. At Whitby, the leachate discharges in a zone of cedars and the impact on the trees is very clear on the imagery. While at Bayview Park, some of the leachate also discharges in a treed area but there is no impact visible on the CIR film, and the tree cover successfully obscures the discharge throughout the year.

c) Season

Seasonal conditions strongly influenced the effectiveness of the CIR imagery in detecting leachate (Figure 11). The maximum information was usually derived in summer, when the vegetation impacts caused by leachate could be recognized on the photographs. The healthy vegetation contrasted well with the generally dry background soils and ground cover on the sites, resulting in better detection of features. However, as on colour photography, the summer vegetation could also cover-up seepage areas.

Detection was difficult in March and November, and despite high soil moisture levels, which should have been clearer on the CIR photos, was usually very incomplete in spring. Lower leachate production volumes

may have been partly responsible for the poor performance of CIR imagery early and late in the year, but poor contrast with the background conditions and the longer shadows cast at this time of year also contributed. The obscuring of areas by shadow was more noticeable on the CIR than on the colour film and was particularly effective in obscuring the main leachate discharge area at Whitby.

5.4.4 Sensor Evaluation

The ability of the colour infrared imagery to monitor leachate discharge varied considerably between sites, and even more between the four seasons. For instance, at Whitby landfill, where the main leachate discharge correlates to heavily damaged tree cover, the summer colour infrared photography clearly delimited the impact area. However, it failed to identify the active seepage and surface staining in other seasons.

At all sites, detection is incomplete, although at some sites only minor discharge goes unidentified. Again, as on the colour photography, some discharge areas are consistently undetected by the CIR imagery, while other discharge is identified in only one season. While some of the discharge impacts were simply too small to be resolved on the photography, many were obscured by vegetation which did not exhibit any stress on the CIR film.

Summer photography produced the best CIR results at the study landfills (Figures 17, 11). Diagnostic features were clearer, because of the greater tonal contrasts, and more abundant because of detection of vegetation stress. At several sites, summer CIR imagery was superior to the summer

colour imagery because of the above characteristics. However, the sensor still failed to clearly detect all discharge areas.

Looking at Figure 11, it is obvious that the CIR sensor was generally not effective in other seasons. In March and November, the observations were generally indistinct or not visible, and at several sites the imagery failed to detect any indications of leachate. Results were slightly better in spring, although still disappointing at most landfill sites.

These seasonal results differ from the observations of Sangrey and Philipson (1978), who found that spring was an effective detection period for the CIR photography. The active study site conditions, particularly the constant regrading of surface materials, may be partially responsible for this difference.

The change in photographic scale from 1:8000 to 1:6000 did not itself appear to significantly increase the ability of the photography to detect leachate. However, considering the small size of most diagnostic features the larger scale (1:6000) is preferable.

5.4.5 Comparison of Colour and Colour Infrared Photography

Neither colour nor colour infrared (CIR) aerial photography could be rated as the "better" sensor for all landfill sites in the study. Looking at Figure 17, the best season for obtaining data was usually spring, for colour detection of leachate impact and summer, for colour infrared detection of impacts. It also appears that colour has a general advantage over colour infrared (Figure 17). However, at some sites,

the colour infrared film provided clearer identification of the leachate discharge than did colour photography from the same season.

The suitability of a sensor in monitoring leachate discharge depends to some extent on the site conditions. For instance, if surface staining is the main indicator (e.g. Oakville) then colour photographs will be superior to colour infrared photographs. However, if vegetation impact is the main indicator (e.g. Whitby), colour infrared film will be superior. For while colour can detect severe impact (i.e. dead trees), such impact is more distinct on summer CIR imagery. In addition, a lower level of vegetation stress can be detected on the CIR.

Unfortunately, neither sensor was able to detect all leachate discharge at each landfill site during one season; and some discharge was not detected by either sensor in any season. Both photography had similar problems in identifying discharge areas as discussed in previous sections, and features were often indistinct or inconclusive. In some cases, more accurate identification of leachate discharge and impacts could be made by using both sensors in one season, or by comparing observations on colour photography at one time of the year with colour infrared observations at another.

However, before any conclusive identification could be made, all observations required field verification.

5.5 Thermography

5.5.1 General Comments

The thermography is able to locate leachate discharge by identifying thermal anomalies around a landfill. The thermography records differences in radiant temperatures, but it cannot distinguish between leachate discharge and natural ground water discharge. Similarly, other features in the environment create thermal anomalies that may appear identical to leachate discharge anomalies. Therefore, field checking must be carried out before a thermal anomaly can be positively identified as leachate discharge.

Thermography cannot identify a landfill site as a landfill site, per se. Hence, in order to interpret the thermography, a geographical base is needed to show the site boundaries and setting. This base can be a detailed map or an aerial photograph. This base then allows the interpreter to orient thermal anomalies with reference to the landfill, and to identify anomalies that are definitely not related to the site. As a result of this comparative interpretation process, the number of field checks is reduced.

5.5.2 Leachate Indicators

Leachate outbreaks appear on the thermography as relatively hot thermal anomalies. The leachate's thermal signatures can vary according to shape, sharpness and brightness. Each of these factors is influenced by season and environmental conditions.

a) Bright Point-Source Signatures

Most of the seepage points found in this study appear on the thermography as point-source emissions. The thermal signatures are characterized as small, bright and distinct thermal anomalies. The signatures vary in size, shape and intensity from site to site and season to season.

On the thermogrpahy illustrations (Figures 20 to 22) seepage points have been disignated by an "A".

Differences in thermal signature at various sites are generally the result of cover phenomena. Whitby (Figure 20) major leachate seepage occurs along the valley wall of Lynde Creek. However, a vegetative cover of coniferous trees results in a mottling effect of the signature. As a result, the sensor, simultaneously detecting both the heat of the seepage point and the cooler overlying tree cover, averages a temperature and assigns a less bright signature to that particular area. In contrast, seepage points along the southwest toe of the Upper Ottawa Street landfill, where there is very little ground cover, are distinct and bright.

Seasonal variations in leachate thermal signatures must also be taken into account in thermographic interpretation. Figure 21 is the thermography of the Upper Ottawa Street landfill for both March and November. In March, the seepage points along the southwest toe of the landfill appear much brighter in contrast to the same seepage points in November. This difference is due to the relative temperature contrasts between the seepage and the ambient temperatures of the surrounding landscape. In March the landfill is cooler

than the surrounding landscape, thereby further enhancing the thermal signature of the outbreaks. In November, the landfill is much warmer than the landscape resulting in less thermal contrast available for leachate detection.

b) Bright-Linear Signatures

Bright (hot), elongated thermal anomalies along the flanks of the landfills correlate with seepage zones where the leachate discharge flowed downslope. These discharge zones are annotated "B" on the thermography examples in the text.

The most prolific discharges can be found on the Burlington and Bayview Park thermography (Figure 22). On the imagery, the source of the outbreak has a thermal influence for some distance downslope. In some cases, a gradual cooling can be detected as the leachate flows away from the site.

These bright-linear signatures varied in intensity at the various sites from season to season. At the Upper Ottawa Street site, leachate flow at the southwest corner can be seen in March, but not in November. This could be related to differences in actual leachate discharge or to differences to thermal contrasts on-site during the different seasons.

Environmental influences on thermal signatures can be detected at the Whitby site. A drainage network from the valley wall to the pond can be seen. The coniferous vegetation overstory in the valley moderates the brightness of the signature by providing less thermal contrast than the cooler deciduous or grass covered landscape.

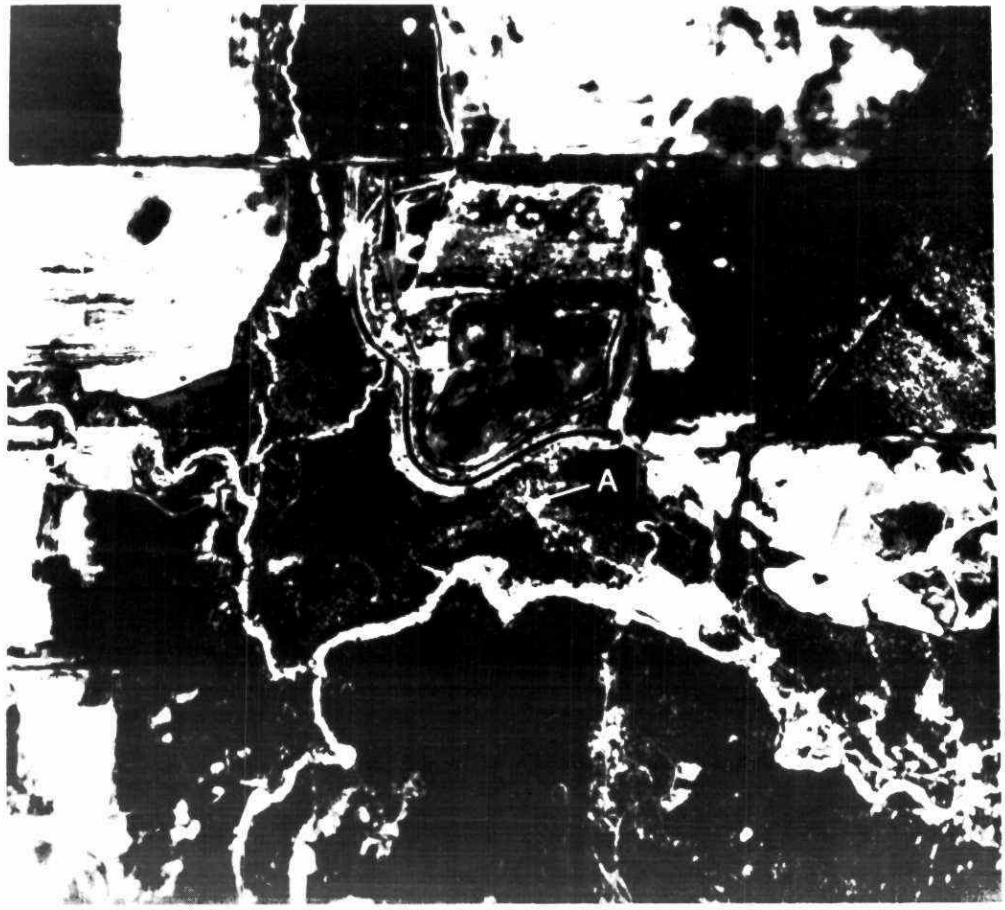
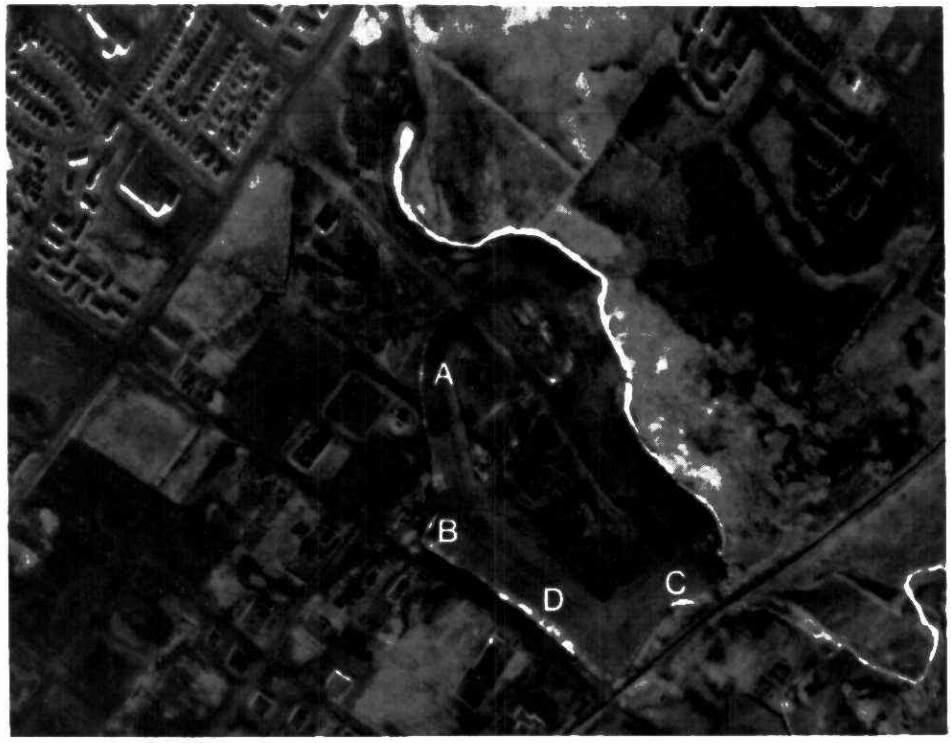


Figure 20 Detailed Level-Slice image R(3-5) of the Whitby Landfill site. Seepage points (A) are barely distinguishable being masked by tree cover. A drainage system for leachate is visible from the seepage points to the pond.



March analogue thermography of the Upper Ottawa Street Landfill site. A - are points of leachate seepage; B - is a linear seepage point; C - is leachate ponding; D - is warm ground.

November analogue thermography of the Upper Ottawa Street Landfill site. The Landfill is warmer than the surrounding landscape. The leachate outbreaks do not appear as substantial as in the March imagery, because of the low thermal contrast.

Figure 21

Figure 22 March analogue thermography of the Burlington Landfill (left) and the Bayview Park Landfill (right);

Burlington Landfill: A - leachate seepage
C - ponding

Bayview Landfill : B - leachate spring

c) Bright-Expansive Signatures

The thermal signatures of ponded areas appear as bright anomalies which are usually expansive. Their shapes conform to the topography and can, therefore, be irregular. The thermal signatures associated with ponding have been marked by "C" on the thermography.

An example of ponding can be seen on the Burlington thermography where, on the west side, in Falcon Creek, the ponding shape is irregular (Figure 22). Ponding also occurs at Upper Ottawa Street, where a large leachate pool is trapped between a berm and the landfill toe (Figure 21). Falcon Creek is less bright because of a partial cover of vegetation. This reduces the normal brightness of the anomaly, and obscures its distinct boundary.

However, the thermography signature does not distinguish leachate contaminated and other surface ponding. In the above examples, the ponding on Falcon Creek is not a leachate pool, while the ponding at Upper Ottawa Street is.

Seasonal variations can be seen on Figure 21. The leachate pond along the northeast toe of the Upper Ottawa Street landfill is very bright and large. In March, partial freezing of the pond surface makes the thermal signature less distinct and gives it a cooler appearance. In November, the pond is ice free and appears uniformly warm across its surface.

d) Lighter Signatures

Warm ground is indicated on the thermography by areas of light, less distinct, grey tones. In many cases, these warm areas resemble a halo around a leachate seepage point. The "warm ground" signatures vary in size, shape and brightness, but are generally distinctly lighter than the surrounding landfill. On the thermography, these warm thermal anomalies are designated "D".

The area along the southwest facing slope of the Upper Ottawa Street landfill is an example of warm ground. In this case, many leachate outbreaks, occurring in relatively close proximity to one another, may be fusing their thermal influence.

Although not apparently site selective, seasonal change seems to affect the warm ground occurrence. The March imagery for Upper Ottawa Street has many more "warm ground" signatures than the November imagery.

5.5.3 Sensor Evaluation

When thermography is available in all three seasons (late winter, spring and autumn), the best results are obtained from the March thermography. This is a period of good thermal contrast between the background ambient temperature and ground water discharge. In the spring, lower thermal contrasts and higher soil moisture reduce contrasts and increase background variation in the image. In November, noise from the data acquisition process unavoidably lowered the quality of the image. As a result, observations were

often not as sharp in these seasons as they were in March, and at some sites thermography provided no information on leachate discharge.

In addition to these seasonal variations in the sensor image, site conditions also determine the effectiveness of thermography. For example, the thermography clearly locates most of the surface discharge at Upper Ottawa Street landfill, although some seepage is masked by the hot anomaly created by Redhill Creek. However, at Whitby the tree cover prevented the sensor from clearly identifying the active leachate seepage zone along the Lynde Creek Valley. As a result, thermography was not particularly useful at the Whitby site.

The thermography was able to locate some discharge that was not easily detected on the photography. These discharges were usually vigorous toe springs, partly obscured by low vegetation, and creating little clear visual impact. In some cases, the thermal anomaly confirmed an inconclusive observation on the photographs.

Our research showed that thermography does not detect all seepage zones at the landfills. Even after level-slicing to enhance the imagery resolution, some discharge identified on the photography cannot be identified on the thermography. Some seeps, usually very small or under heavy vegetation cover were not detected on any imagery, but only by field checking.

The thermography appears to be most effective when used in conjunction with a photographic sensor. In this combination the thermal anomalies can be located and the ground conditions at that point determined by photo interpretation techniques. Since the imagery does not distinguish landfill and non-landfill related features, analyses of the

photography is particularly important in identifying whether it is possible to have leachate discharge occurring at any location. Furthermore, the thermogrpahy can be used to confirm photographic detection of probable leachate discharge, although field checking is still required.

Finally, however, the thermography and the photographic sensors are not able to locate all leachate discharge. With varying effectiveness, at different sites and in different seasons, these remote sensing techniques can monitor some of the leachate discharge. Their most useful application, however, is to help in the planning of field checking programs. It is important to understand that none of the remote sensing techniques can either singly or in combination replace on-site checking of leachate discharge conditions.

6. CONCLUSIONS

This research program has allowed the investigators to make the following conclusions.

1. Remote sensing is a useful technique in searching for new landfill locations, assessing and monitoring operating facilities and monitoring closed sites.

2. Of the four remote sensing systems evaluated - i.e., archival photography, colour, colour infrared, and thermography - archival photography proved to be the most cost-effective, the most readily available and the easiest to use for the assessment of landfill sites.

3. Archival black and white photographs provide a time-lapse review of site and surrounding conditions. These photographs are best suited for the evaluation of former landfills and the assessment of historical information at existing facilities. For maximum information the interpreter should have a sound background in the terrain sciences, hydrogeology and site operations techniques. Photogrammetrically derived contour maps and base plans can be obtained from archival photographs; however, the small scales of most of these photographs may provide considerable constraint to contour mapping.

4. Colour aerial photographs provide the second most cost--effective technique. These photographs are not as readily available from government libraries as the archival photographs, and in most cases, they must be specially flown. They can, however, be used for the interpretation of existing surface leachate migration conditions as well as for the monitoring of site

operations. Colour imagery is easier to interpret than the black and white, especially for the novice, and basic interpretation techniques, such as the identification of red-brown leachate, are easily taught. Colour photographs can also be used to photogrammetrically derive contour and base plans.

5. Colour Infrared Photographs are effective in assessing the state of stress in vegetation surrounding a landfill site. This stress is detected best in summer imagery. The photographs can be viewed stereoscopically in three dimensions but they are more difficult to interpret than either colour or black and white. Colour infrared imagery does not provide a suitable source for photogrammetrically derived contour maps and base plans.

6. Thermography can detect thermal anomalies on the ground surface. Through field verifications some of these anomalies can be related to leachate springs. Pre-dawn flights appear to be the optimum times to expose this imagery. The imagery, however, cannot be viewed in three dimensions. Both on-site field verification and interpretation of conventional photography are necessary to assess the significance of the anomalies. Thermography is more difficult to properly interpret than the other sensors examined in this program. Special equipment, such as a density slicer, is often required to obtain optimum results from the imagery. During the time of this research (1979 to 1981) there was only one company in Canada with the ability to obtain thermographic imagery. This resulted in a lack of competitive bidding for the cost of the imagery, problems in scheduling of the flights and delays in receiving the processed imagery.

7. Field visits are essential to properly explain the phenomena interpreted from the imagery. Remote sensing alone cannot replace field studies.

8. We found that there was no one feature or group of features that provided consistent diagnostic clues to the identification of landfill related impacts. Rather we conclude that the interpreter of the imagery must have a clear understanding of terrain sciences, hydrogeological principles and landfill operations and their cause-effect relationship relative to the environment.

9. Existing archival photography should always be reviewed first. If special flights are then necessary, it is most cost-effective to expose both colour and colour infrared from two camera mounts within the same aircraft. If the aircraft is fitted with only one mount, then colour aerial photographs should be taken.

10. We conclude that a scale of 1:6000 is suitable for the imagery studied.

11. Figure 23 is a comparison of the four remote sensing techniques investigated, identifying aquisition criteria, diagnostic features, advantages, limitations and potential applications for each sensor.

12. None of the four sensors detected any gas migration impact around the six landfill sites.

Figure 23 REMOTE SENSING AND WASTE MANAGEMENT

Sensor	Acquisition Criteria	Diagnostic Features	Advantages	Limitations	Applications

Archival Black & White Photography	• historical coverage
	• 5± year time sequence
	• scale 1:10000 - 1:20000
		• former landfills
		  • disturbed land surfaces
		  • topographic and drainage changes
		  • indication of fill materials (piles of refuse, etc.)
			• relatively accurate location of former landfilling activity
			• background physical setting and operations data on existing landfills
			• predict potential leachate discharge areas and other potential environmental impacts
			• readily available
			• inexpensive
				• key information may be missed because of time gaps in coverage, too small scale or visual effects of other activities near site
				• should be combined with other data for maximum use
				• interpretations must be field checked
				• requires experienced interpreter for maximum data
				• not indentify current impacts
					• Identification and assessment of former Landfills
					• background data for landfill closure designs
					• planning site location

Colour Photography	• current coverage
	• spring or summer optimum period
	• scale 1:6000± or greater
		• surface staining
		• surface wetness on or at toe of site
		• vegetation gaps and stress
		• gaps in snow cover
			• visual record of current landfill conditions, including operations (if active), revegetation and cover conditions (if closed), surrounding environment
			• locate some active leachate discharge areas and associated visible impacts
			• best sensor for detecting leachate staining
			• identify physical setting
			• moderate cost for acquisition and processing
			• readily available by special contract
				• diagnostic features of leachate are not unique and are often indistinct
				• detection of leachate discharge often incomplete because:
				  • small visual impact or impact obscured by vegetation
				  • off site impact more difficult to identify
				• must be specially acquired
				• requires experienced interpreters for maximum data although easier for novice to interpret than black and white photos
					• Monitoring post-closure conditions
					• Monitor landfill operations

Figure 23 REMOTE SENSING AND WASTE MANAGEMENT

Sensor	Acquisition Criteria	Diagnostic Features	Advantages	Limitations	Applications

Colour Infrared Photography	• current coverage
	• specially acquired
	• summer optimum period; late spring suitable at some sites
	• scale: 1:6000± or greater
		• vegetation stress (positive and negative)
		• vegetation gaps
		• surface wetness on or at toe of landfill
		• snow gaps
		• surface staining (poor)
			• identify present landfill conditions (including operations, surrounding environment, closure)
			• excellent for detecting vegetation stress (positive and negative) for impact and site rehabilitation purposes
				• diagnostic features of leachate impact are not unique and are often indistinct
				• detection of leachate impact is often incomplete because
				  • small visible impact
				  • obscured by overhanging vegetation
				  • vegetation readjusts to new conditions
				• results must be field checked
				• vegetation stress may be inconclusive; require developing pattern over several years
				• moderate cost; slightly greater than colour to process prints.
				• false colour requires greater experience in interpretation
				• colour variations in film require stricter processing control and greater experience when comparing photos
					• Post-operational monitoring
					o Operations monitoring

Thermography	• current coverage • specially acquired • pre-dawn during late autumn or late winter • scale: comparable to air-photos	• bright "hot spots" against dark (black or grey) cold background	• identify small and usually indistinct leachate discharge points	• sensor measures temperature only; diagnostic features are not unique and often inconclusive • detection of leachate discharge incomplete • no temperature distinction between landfill and surrounding lands • necessary to have detailed map or aerial photography to identify ground locations • results must be field checked • interpretation requires experience and special processing • expensive to acquire; only one supplier at this time	• not recommended for application at this time

7. RECOMMENDATIONS

Based on the conclusions of this research study, there are a number of recommendations that can be made regarding the uses of remote sensing in waste management programs in Ontario. These recommendations are divided into three programs:

1. assessment of former landfill sites,
2. monitoring of operating facilities,
3. post-closure monitoring.

7.1 Assessment of Former Sites

7.1.1 Recommendation

We recommend that the use of archival, black and white photographs available from government libraries be integrated into the Ministry of the Environment's Waste Site and Industrial Waste Site Identification Studies programs.

7.1.2 Background

In 1979 the Ministry of the Environment initiated a province-wide survey of waste disposal sites which were in operation prior to the declaration of the Waste Management Act (1970). The purpose of the survey was to develop a master list of waste disposal sites to determine potential environmental and public safety hazards. The program was called the Waste Site Identification Study. Phase I, Site Inventory, of this study was carried out by three universities in the province under contract to the government. Phase II of the study involved the preliminary field assessment of selected sites during 1980 and a more detailed site

verification investigation during 1981. Phase II was carried out by consultants under contract to the government.

These initial studies did not include waste disposal sites operated by industry for their manufactured by-products. In 1980, regional representatives of the Industrial Abatement Section of the Ministry documented candidate industrial waste disposal sites which warranted study within their respective Districts. Contracts were awarded to consultants to investigate the public safety and environmental hazard potential of each.

These initial studies did not include waste disposal sites operated by industry for their manufactured by-products. In 1980, regional representatives of the Industrial Abatement Section of the Ministry documented candidate industrial waste disposal sites which warranted study within their respective Districts. Contracts were awarded to consultants to investigate the public safety and environmental hazard potential of each.

Even though both of these programs are well advanced, it is still possible and advisable to integrate a remote sensing component into them.

Of a total of 3475 known sites within the province, 1523 are open and certified (June 1979), 1451 are closed and of these 1451 sites, 177 have been rated as priority number one (#1) sites.

We recommend that archival, black and white aerial photographic coverage be obtained for all sites with the exception

of the 177 priority #1 sites that are already in the second phase of investigation. Implementation of this program is described in the following paragraphs.

7.1.3 Implementation

a) Obtain existing black and white aerial photographs from the archives of both the Ontario Ministry of Natural Resources and the National Air Photo Library in Ottawa. Stereo coverage is required and it should date from the pre-landfilling period to the present or most recent photography. Scale of 1:20,000 or larger is preferable.

b) Stereoscoping interpretation of each set of photographs should be undertaken by an experienced interpreter. The following information should be delineated on the airphotos;

i) areas (and type) of disturbed land,

ii) areas (and type) of landfilling,

iii) areas (and type) of topographic change related to the landfill,

iv) areas (and type) of drainage changes related to the landfill,

v) description of hydrogeological terrain units and delineation of their areas,

vi) description of land use and changes in land use during the years,

vii) estimate of type of waste through inductive and general and particular deductive interpretation techniques.

c) Information for each successive year should be plotted on an overlay over an appropriate base map.

d) The changes that have taken place over the years should be evaluated in terms of the probability of off-site impact due to leachate and gas migration.

e) Each of the sites should be given a priority rating, based on the following general criteria:

i) susceptibility of the physical environment to the natural migration of off-site contamination and gas;

ii) suspected types of refuse (i.e., domestic, solid or liquid industrial, tannery wastes, wood wastes, etc.);

iii) relative size of facility;

iv) present land use as derived from the most recent air photos, and the chronology of such land use relative to the developmnet of the landfill site.

f) With this information derived from the archival photography it is now possible to place a priority of action on the sites and to design specific field identification and verification procedures. Such procedures are being carried out for the original 177 priority #1 sites identified by the universities.

g) It is possible to use archival photography to supplement the search for closed sites in areas where the original

inventory was not conducted or where the original inventory showed a lack of information. In these areas it is recommended that archival air photo coverage be obtained from the government libraries. Then the entire areas surrounding the chosen urban centres should be interpreted, looking specifically for changes in landform patterns, filling of aggregate pits or building of fills that may indicate old landfilling or garbage dump operations. Once potential sites are identified then implementation of stages 'B' to 'F' previously described, can be carried out.

7.2 Monitoring of Operating Facilities

7.2.1 Recommendation

We recommend the photographing in colour and colour infrared* during the late Spring or early Summer of every year at an approximate scale of 1:6000, or larger, of selected large landfills within the Province.

7.2.2 Background

At the present time some of the regional governments and other municipalities within the province have their major landfills flown on a regular basis. The main purpose of these flights is to obtain stereoscopic black and white air photo coverage as a basis for photogrammetric measurements of fill quantities and site changes. These flights can also

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* **If the aircraft does not have two camera ports then colour is preferable to colour infrared film.**

provide vital information for monitoring the continued operations of the facility. It has been found, however, that it is most cost-effective to monitor using remote sensing where the imagery can also have a second use, such as photogrammetric mapping. This double use of the photographs is feasible on the larger landfills - private, municipal and industrial - within the province.

Such a program will require cooperation between provincial and municipal levels of government and between provincial officials and private operators. The monitoring results derived from the air photo interpretation will aid in the regulatory functions while the photogrammetric measurements will be useful in the operational functions at the site. Information derived from sequential aerial photographs provides a permanent historical record of operational and abatement measures at landfills. Examples of some such data are as follows:

- Accurate data on remaining site life and operations efficiency is critical to municipal planning and budgeting for long-term waste management needs.

- Compliance with standard "housekeeping" and operational requirements at a site can be checked; this would apply to both municipal and private operators.

- Problems arising during operations or following closure can be evaluated in the light of past operations, and the data used in remedial measures design.

- Landfill operations methods can be evaluated with regard to conditions at the site (efficiency, environmental impact) and improvements made to the design and operation of future sites.

Cost effectiveness depends upon the uses of the data. Considering the high cost of landfill operation and the higher cost of landfill licensing, the cost of aerial photograph acquisition and analyses is quite small. Contour mapping and capacity calculations require specialized equipment and analyses. However, other general operations evaluations can be readily obtained from the photographs.

7.2.3 Implementation

The following is a general outline of a landfill operation monitoring program. This program would be cost-effective either for large municipal governments where data acquisition could be combined with regular land use photographic programs and where several municipalities can share acquisition costs because landfills are relatively close together.

Program Outline

1. Stereo photography should be obtained in late spring or early summer of every year during the operational life of the landfill. More frequent intervals may be warranted on larger landfills where a closer control of volumes is required.

2. Photographic scales of 1:6000 or larger are recommended. The exact scale will be dictated by the photogrammetric requirements.

3. If the contract aircraft has more than one camera mount and port, then colour and colour infrared photography are recommended. If only one port is available, then we recommend using colour film.

4. The ground areas to be covered by the photography should provide coverage down gradient from the site and sufficient perimeter coverage to allow the interpreter to evaluate the landfill in relation to the surrounding terrain.

5. Stereoscopic interpretation of the coloured air photos will identify the following operation features -

   i) extent of landfilling,

   ii) configuration of working face,

   iii) site works construction (on-going drainage, road access, etc.),

   iv) extent of earth cover application,

   v) rate of site utilization,

   vi) record of operation sequencing,

   vii) location and extent of site excavations, berms, cover stockpiles,

   viii) operational practices (burning, litter spread),

   ix) leachate discharge and ponding on site,

x) location of any suspected leachate outbreaks and a time-lapse surveillance of changes in vegetation conditions (especially if colour infrared is used).

6. The colour aerial photographs can also be used as the stereographic base for automatic contour mapping and the calculation of changes in earth works and garbage quantities.

7.3 Post-Closure Monitoring

7.3.1 Recommendation

We recommend the post-closure monitoring, using colour and colour infrared*, of landfills previously designated as having potential impact on surrounding lands.

7.3.2 Background

Through the priority rating system developed in the Waste Site Identification Study program and through cooperation with the municipalities and private operators, candidate sites for post-closure monitoring can be selected. The criteria for selection of these sites will have to be developed on a rational technical basis. Development of these criteria is outside of the scope of this report.

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* **If the aircraft does not have two camera ports and mounts, then the exposure of infrared film is optional.**

Post-closure monitoring will help officials evaluate the success of the closure designs and appraise them on a yearly basis for any potential impact on off-site lands and waters. Specially acquired colour and colour infrared photography can be effective in these programs, particularly when linked with the photographic record of operations. Surface discharge of leachate as a result of collection system failure can be monitored and site revegetation success evaluated. In addition, the photography provides a permanent visual record of site conditions. Comparison of this record can be useful in detecting impacts causing a gradual change, (i.e., slow degradation of tree cover around site perimeter due to gas migration) that might be missed during field visits. This record also allows continuity of monitoring data despite changes in supervisory and field staff and can allow re-evaluation of the site if conditions change many years after the landfill closure. However, aerial surviellance alone is not adequate for post-closure monitoring, since only clear visual surface impacts will be detected on the photographs. Field monitoring is necessary with the aerial photography.

As with the operational monitoring, the program is most suitable and cost-effective for large municipalities where data acquisisition can be combined with land use data or where several municipalities can share acquisition costs.

7.3.3 Implementation

The following is a general outline for a post-closure monitoring program with aerial photography.

Program Outline

1. Aerial photography coverage should be obtained every one to two years. Late spring or early summer is the best period for acquisition.

2. Colour and colour infrared film should be used; colour is preferable if failure of the collection system will result in surface staining of landfill, colour infrared is preferable if impacts are likely to affect vegetation.

3. Photographic scale should be about 1:6000.

4. Stereoscopic coverage should include the area immediately around the site and down gradient of the site. Distance down gradient will depend on setting.

5. When photography is obtained it should be analysed for -

   i) site condition (revegetation, etc.)

   ii) possible leachate discharge -

   - staining
   - wetness
   - vegetation gaps/stress

6. Each analyses should be compared with previous data to see if patterns are developing at the site.

7. Close to acquisition time, the site should be field checked to verify photographic observations and to check that impacts have not been missed.

8. Observation points should be located on the photographs (or on overlays). This allows accurate location of field data and comparison of field observations with photographic appearance.

9. Annual or biannual data provides a continuous record of the site which can be used by any member of the municipality or ministry staff at any time to re-assess past waste management programs and performance.

BIBLIOGRAPHY

Anonymous: (1979a) Cornell Remote Sensing Newsletter. Vol. 7 No. 6. 1979a February 1979.

Anonymous: (1979b) Geraghty & Miller Inc., Newsletter. Vol. 1 No. 4. 1979.

Antrop, M. and Daels, L.; (1978) Determination of Geographical Surfaces Caused by Vegetation Damage; p. 2095-2103 in Proceedings, International Symposium for Observation and Inventory of Earth Resources and the Endangered Environment. Vol. 2. International Society for Photogrammetry, Commission VII, Freiburg, Germany, p. 178, 2395 p.

Avery, T.E., (1968) Interpretation of Aerial Photographs. Second Edition. Burgess Publishing Company, Minnesota, 324 p.

Bird and Hale Limited, (1977) Surveillance of the Environmental Effects of a Highway Facility by Remote Sensing: A State-of-the-Art. Ontario Ministry of Transportation and Communications, Research and Development Division, Research Report 209, 74 p.

Brooks, H.K., Ruth, B.E., and Degner, J.D., (1977) Basic Hydrogeologic and Remote Sensing Data for Selection of Sanitary Landfill Sites. Florida University, Department of Geology, 28 p.

Bristow, M.P.F., (1978) Airborne Monitoring of Surface Water Pollutants by Fluorescence Spectroscopy; Remote Sensing of Environment. Vol. 7 No. 2. p. 105-127.

Bush, P.W. and Collins, W.G., (1974) The Application of Aerial Photography to Surveys of Derelict Land in the United Kingdom; p. 167-181 in Environmental Remote Sensing: Applications and Achievements. Bristol Symposium on Remote Sensing, Bristol 1972. Barrett, E.C. and Curtin, L.F. (eds.), 309 p.

Canadian Centre for Remote Sensing, (1977) Information Bulletin - Airborne Operation. Canada Centre for Remote Sensing, Department of Energy, Mines and Resources, Ottawa, Ontario, Canada.

Daedalus, (1977) Instruction Manual for DEI-612 Signal Processor. Daedalus Enterprises Limited, Ann Arbor, Michigan, U.S.A.

BIBLIOGRAPHY

(continued)

Dalstead, K.J. and Worcester, B.K., (1979) Detection of Saline Seeps by Remote Sensing Techniques. Photogrammetric Engineering and Remote Sensing. Vol. 45 No. 3. p. 285-291.

Deutsch, M. and Estes, J.E., (1980) Landsat Detection of Oil from Natural Seeps; Photogrammetric Engineering and Remote Sensing. Vol. 46 No. 10. p. 1313-1322.

Enslin, W.R., Hill-Rowley, R., and Tilmann, S.E., (1977) Application of Aerial Photography to Water-related Programs in Michigan; p. 807-816 in Proceedings of 11th International Symposium on Remote Sensing of the Environment. Vol. 2.

Erb, T.L., Philspon, W.R., Teng, W.L. and Liang, Ta., (1981) Analysis of Landfills with Historic Air Photos. Photogrammetric Engineering and Remote Sensing. Vol 47, No.9, pp. 1363-1369.

Fleming, J., (1980) Standardization Techniques for Aerial Colour Infrared Film. The Interdepartmental Committee on Air Surveys and The Surveys and Mapping Branch, Department of Energy, Mines and Resources, Ottawa, Ontario, Canada.

Garofalo, D. and Martin K.R., (1977) Regional Energy Availability from Conversion of Solid Waste. Photogrammetric Engineering and Remote Sensing. Vol. 43. p. 727-783.

Garofalo, D. And Wobber, F.J., (1974) Solid Waste and Remote Sensing. Photogrammetric Engineering. Vol. 40 No. 1. p. 45-59.

Gartner, J.F., (1980) Recent Canadian Experience in Communicating Terrain Evaluation Information. International Association of Engineering Geology, Bulletin No. 21. p. 164-174.

Gartner Lee Associates Limited, (unpublished) Remote Sensing Methodology for the Location of Abandoned Landfills in the City of Ottawa. Preliminary Internal Report. 2 p.

Gibb, J.P. and Cartwright, K., (1976) Field Verification of Hazardous Waste Migration from Land Disposal Sites. National Conference Disposal of Residues on Land, St. Louis. p. 179.

BIBLIOGRAPHY

(continued)

Gibson, L.J., (1974) The Application of Aerial Photographic Interpretation to Derelict Land Studies in South Wales; p. 389-401 in Proceedings: Symposium on Remote Sensing and Photo Interpretation. International Society for Photogrammetry. Vol. 1. Banff 1974.

(1978) Remote Sensing Applications and The Work of the Remote Sensing Unit at the University of Aston; p. 1439-1454 in Proceedings: International Symposium on Remote Sensing for Observation and Inventory of Earth Resources and the Endangered Environment. Vol. 2. International Society of Photogrammetry, Freiburg, Germany 1978. 2395 p.

Halstead, E.H. and Rennie, D.A., (1972) Experiment Program on Remote Sensing for Crop Identification and Pollution Detection; p. 83-93 in Proceedings: First Canadian Symposium on Remote Sensing. Vol. 1. Ottawa, Ontario. February 1972.

Harvey, E.J.; Williams, J.H., and Dinkel, T.R., (1977) Application of Thermal Imagery and Aerial Photography to Hydrologic Studies of Karst Terrain in Missouri. Geological Survey of Missouri. 66 p.

Hill, J.M. and Trivedi, Mohan, (1979) Location Verification of Waste Impoundments in Louisiana Using Aerial Imagery. National Conference on Hazardous and Toxic Wastes Management, June 3-5, New Jersey.

Hunt, R.E.; Interpretation of Remote Sensing Imagery, (1975) A Tool for Land Use Planning and Protection. Consulting Engineering. Vol. 44 No. 6. p. 54-59.

Johnson, R.W., Glasgow, R.M., Duedall, I.W., and Proni, J.R., (1979) Monitoring the Temporal Dispersion of a Sewage Sludge Plume. Photogrammetric Engineering and Remote Sensing. Vol. 45 No. 6. p. 763-768.

Kennedy J.M. and Wermund, E.G., (1971) Oil Spills, IR and Microwave. Photogrammetric Engineering. Vol. 37 No. 12. p. 1235-1242.

Kodak, (1972) Kodak Aerial Films and Photographic Plates. Eastman Kodak Company, Rochester, New York, U.S.A.

BIBLIOGRAPHY

(continued)

Lawrence, G.R., White D., and Deslauriers, I., (1980) The Detection of Groundwater Discharges (Springs) Using Aerial Thermography. Proceedings, Sixth Canadian Symposium on Remote Sensing, Halifax, Nova Scotia.

Lillesand, T.M. and Kiefer, R.W., (1979) Remote Sensing and Image Interpretation. John Wiley & Sons.

Mathur, B.S. and Gartner, J.F., (1968) Principles of Photo Interpretation in Highway Engineering Practice; Ontario Department of Highways, Materials Testing Division, Course Manual; 236 p.

Meyer, William and Welch, R.I., (1975) Water Resources Assessment; Chapter 19, p 1479-1551 in Manual of Remote Sensing, R.F. Reeves, Abraham Anson and David Lanson (eds.); American Society of Photogrammetry, 2144 p.

Murtha, P.A., (1978) Remote Sensing and Vegetation Damage: A Theory for Detection and Assessment; Photogrammetric Engineering and Remote Sensing, Vol. 44, No. 9. p. 1147-1156.

Myers, V.I., (1975) Crops and Soils, Chapter 22, p. 1715-1813 in Manual of Remote Sensing, R.G. Reeves, Abraham Anson, and David Landen (eds.), American Society of Photogrammetry, 2144 p.

Myers, V.I.; Heilman, M.D., Lyon, R.J., Namken, L.N., Simonett, D., Thomas, J.R., Wiegand, C.L. and Wooley, J.T., (1970) Soil, Water and Plant Relations; p. 253-279 in Remote Sensing with Special Reference to Agriculture and Forestry, National Academy of Sciences, Washington, D.C.

North, G.W., (1971) Remote Sensing for Pollution and Environmental Quality Studies; p. 973-987 in Proceedings, Seventh International Symposium on Remote Sensing of Environment, Vol. 2. Ann Arbor, Michigan.

Ontario Centre for Remote Sensing, (1978) The Monitoring of Sanitary Landfill Sites Using Remote Sensing Techniques: A Preliminary Report; OCRS Report, Ontario Ministry of Natural Resources, 32 p.

Ontario Centre for Remote Sensing, (1979) Ministry of Natural Resources Annual Review 1978-79. OCRS. Queen's Park, Toronto, Ontario.

BIBLIOGRAPHY

(continued)

Paul, C.K.; (1977) Remote Sensing of Environmental Impact of Land Use Activities; p. 363-377 in Proceedings, 11th International Symposium on Remote Sensing of Environment, Vol. 1. Ann Arbor, Michigan, April 1977.

Philipson, W.R., (1976) Remote Sensing of Ground and Surface Water Contamination by Leachate from a Landfill; in Prodeedings, International Conference on Environmental Sensing and Assessment. Vol. 1. New York; Institute of Electrical and Electronics Engineers, 5 p.

Philipson, W.R. and Sangrey, D.A., (1977) Aerial Detection Techniques for Landfill Pollutants; Third Annual EPA Research Symposium on Management of Gas and Leachate in Landfills; St. Louis, Missouri.

Reeves, R.G., ed., (1975) Manual of Remote Sensing. American Society of Photogrammetry; Falls Church, Virginia.

Sabins, F.F., (1978) Remote Sensing Principles and Interpretation. W.H. Freeman and Company, San Francisco, California.

Sangrey, E.A., Teng, W.L., Philipson, W.R., and Liang, Ta, (1975) Remote Sensing of Ground and Surface Water Contamination by Leachate from Lnadfill; Paper 15-1, in Proceedings, International Conference of Environmental Sensing and Assessment, Las Vegas, Nevada.

Schneider, S., (1977) Operational Remote Sensing Systems for Environmental Monitoring and Regional Planning; p. 373-378 in Earth Observation Systems for Resource Management and Environmental Control, D.J. Clough and W.W. Morley, (eds.), Plenum Press, New York.

Souto-Maior, J., (1973) Applications of Thermal Remote Sensing to Detailed Ground Water Studies; p. 284-298, in Remote Sensing and Water Resources Management; American Water Resources Association Meeting, 1973, Burlington.

Terra Scan Limited, (1972) Special Report of the Role of the Geologist and Remote Sensing Techniques in The Northern Roads Program; prepared for Technical Services Branch, Department of Indian Affairs and Northern Development, Ottawa. 18 p. plus appendices.

BIBLIOGRAPHY

(continued)

Vass, P.L. and Van Genderen, J.L., (1978) Monitoring Environmental Pollution by Remote Sensing; p. 2125-2142 in Proceedings, International Symposium on Remote Sensing for Observation and Inventory of Earth Resources and the Endangered Environment. Vol. 2. International Society for Photogrammetry, Commission VII, Freiburg, Germany, 1978; 2395 p.

Vizy, K.N., (1974) Detecting and Monitoring Oil Slicks with Aerial Photos; Photogrammetric Engineering. Vol. 40 No. 6. p. 697-708.

Washburn, J.F. and Sandness, G.A., Detection, (1977) Identification and Quantification Techniques for Spills of Hazardous Chemicals; p. 1629-1635, in Proceedings, 11th International Symposium on Remote Sensing of Environment. Vol. 2. Ann Arbor, Michigan.

Watson R.D., Hemphill, W.R. and Bigelow, R.C., (1975) Remote Sensing of Luminescing Environmental Pollutants Using a Fraunhofer Line Discriminator (FLD); p. 203-222 in Proceedings, Tenth International Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, Michigan, 1975.

Wells, W. and Bourque, H., (1980) The Future: What Will Work? Paper presented at Panel Discussion, Second Canadian Conference on Solid Waste, Winnipeg, October 15-17, 1980.

Wolfe, W.L. and Zissis, G.J., (1978) The Infrared Handbook. The Infrared Information and Analysis Centre, Environmental Research Institute of Michigan. Ann Arbor, Michigan.

Zsilinszky, V.G., (1969) Supplementary Aerial Photography with Miniature Cameras. Photogrammetria, Volume 25 (1969/1970); p. 27-38.

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